Army Research Laboratory

Examination of Nonchromate Conversion Coatings for Aluminum Armor From Three Final Candidates Using Accelerated Corrosion and Adhesion Test Methods

by Brian E. Placzankis, Chris E. Miller, and Bill D. Mullis

ARL-TR-2601 September 2001

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

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Abstract

This study examines the effectiveness of three final candidate nonchromate conversion coatings on aluminum alloys 5083, 7039, and 6061 coated with standard solvent-based Chemical Agent Resistant Coating (CARC) system. The nonchromate conversion coatings examined were: Cape Cod Organosilane, Brent Oxsilan AL-0500, and Henkel Alodine 5200. Evaluation methods included: American Society for Testing and Materials (ASTM) standard B117 (ASTM. "Standard Method of Salt Spray [Fog] Testing." ASTM B117, West Conshohocken, PA, 1990) salt fog, General Motors (GM) 9540P (GM. "Accelerated Corrosion Test; GM 9540P." GM 9540P, GM Engineering Standards, 1997) cyclic salt spray, ASTM D3359A (ASTM. "Standard Test Methods for Measuring Adhesion by Tape Test." ASTM D3359, West Conshohocken, PA, 1987) wet adhesion, ASTM D3359B dry adhesion, ASTM D4541 (ASTM. "Standard Test Method for Pull-Off Strength of Coated Specimens Subjected to Corrosive Environments." ASTM D4541, West Conshohocken PA, 1989) pull-off adhesion, and exposure at the U.S. Army Aberdeen Test Center (ATC) automotive test track. Specimens examined consisted of flat test panels as well as actual components used in M2/M3 Bradley Fighting Vehicles Systems. Additional panels and components were exposed for 4000 mi on actual fielded Bradleys at Camp Roberts, CA, and examined after exposure for degradation and adhesion. The ultimate goal of this study is to choose the best overall substitute for hexavalent chromium based Alodine 1200 which is currently in use and is known to be harmful to the environment and a health hazard.

Acknowledgments

The authors would like to thank the following people who contributed to this study: Rick Garrison of the U.S. Army Aberdeen Test Center (ATC) Automotive Test Track who assisted with securing the test panels and Bradley components to a Family of Medium Tactical Vehicles (FMTV) test vehicle; Al Loew from Program Manager (PM) FMTV for taking time from his own study to help in obtaining clearance from the PM's office for attaching test panels and Bradley components to an FMTV test vehicle; Heidi Nicely and Dave Brader of Concurrent Technologies Corporation for providing additional information and support in the application stages of the pretreatments; and Jim Dorsch of United Defense Limited Partnership for exposing and tracking of the panels and components on the fielded Bradleys. Finally, we thank Ben DeMarco and Geoff Hoerauf of the Bradley Fighting Vehicle Systems Environmental Management Team and Tom Landy of the U.S. Army Tank-Automotive Research, Development, and Engineering Center (TARDEC) for sponsoring this study.

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1. Introduction

Three final candidate nonchromate conversion coatings were selected from a group of six original candidates, based upon feedback from the Bradley Fighting Vehicle Systems (BFVS) Environmental Management Team (EMT) and from previous EMT-sponsored studies performed by the U.S. Army Research Laboratory (ARL) [1–3]. Criteria for final consideration included corrosion and adhesion performance, as well as economic feasibility and scaleabilty to extremely large baths capable of treating an entire Bradley vehicle hull. Aluminum alloys 5083, 7039, and 6061 were selected by the committee for investigation with the chromate conversion coating alternatives. As in the prior study, all candidate vendors agreed to have their products evaluated and supplied the pretreatment materials. In an effort to maintain consistency and equal application conditions, all vendors traveled to Concurrent Technologies Corporation in Johnstown, PA,* and supervised the pretreatment as well as the coating stages of specimen preparation.

2. Experimental Procedure

Aluminum panels (39 each nominally 10 cm × 15 cm × 0.6 cm) of alloys 5083-H131 and 7039-T64 were machined from rolled armor plate stock. A similar quantity of aluminum 6061-T6 industry standard test coupons were also obtained. All coupons were clearly labeled using a mechanical die to permanently indent the experimental designation. Thirteen panels with each conversion coating combination were prepared. From each set of 13 panels, 10 were sent to ARL—three for American Society for Testing and Materials (ASTM) standard B117 [4] salt fog, three for GM 9540P [5] cyclic corrosion, one for laboratory adhesion (ASTM D3359 A and B [6] and ASTM D4541 [7]), and three for exposure at the Aberdeen Test Center (ATC) automotive test track [8, 9]. The three remaining panels were sent for mounting and fielded durability exposure on actual Bradley vehicles stationed at Camp Roberts, CA. In addition to panels, actual components used on Bradleys were treated with the candidates and distributed for laboratory, test track, and field exposure. The components consisted of headlight guards, taillight guards, antenna brackets, and access covers. All of the Bradley components were grit blasted prior to the pretreatment stage to clean and remove prior coatings. A detailed breakdown of the panel and component distribution as well as numbering schemes are listed in

*Concurrent Technologies Corporation, 100 CTC Drive, Johnstown, PA 15904.

Tables 1–3. Personnel from each of the pretreatment vendors were present during the surface prep, pretreatment, and coating application stages (Tables 4–6) to ensure equal and optimal conditions for the pretreatment candidates. Following the cleaning and pretreatment stages, all of the panels and components were coated using standard Chemical Agent Resistant Coating (CARC) consisting of MIL-P-53022 [10] epoxy primer and MIL-C-53039 [11] topcoat. One component, an access cover for the Bradley bilge pump, was topcoated with seafoam green MIL-C-22750 [12] which is used for interior Bradley surfaces.

Salt fog testing in accordance with ASTM B117 [4] was used to screen the CARC-coated panels. The solution used was the standard 5% NaCl. All panels were photographed prior to testing, upon significant changes, and at failure. The panels, (three each) for each conversion coating, were exposed for 3000 hr of salt fog. These panels were "X" scribed using a standard carbide-tipped hardened steel scribe. Figure 1 shows a representative photo of initial specimen appearance after scribing (all painted panels appeared visually identical before testing). Final detailed ratings for the 3000-hr duration were assessed using ASTM D1654A [13] which quantitatively indicates the damage caused by pitting or delamination outwards from the scribe (Table 7).

A cyclic corrosion test chamber (CCTC) was used to evaluate the CARC-coated test panels and Bradley headlight guards. For each conversion coating tested, three primed and topcoated CARC panels were subjected to CCTC testing. As in salt fog, the panels were X scribed. The scribed panels were placed into the chamber (Figure 2) and tested using GM Standard Test 9540P [5], method B, which provides a more realistic accelerated environmental test than conventional salt fog [14]. The standard 0.9% NaCl, 0.1% $CaCl_2$, 0.25% $NaHCO_3$ test solution was used. The 9540P test consists of 18 separate stages that include the following: saltwater spray, humidity, drying, ambient, and heated drying. The environmental conditions and duration of each stage for one complete 9540P [5] cycle are provided in Table 8. In addition, standard plain carbon steel calibration coupons described in 9540P [5] and supplied by GM were initially weighed and subsequently monitored for mass loss at intervals set by the specification. Mass losses measured for steel coupons used for this test were within acceptable parameters stated in the GM specification (Table 9). The panels were photographed or digitally scanned prior to testing, upon significant observations, and at the suspension of the testing (120 cycles). As with B117 [4] salt fog, the extent of damage was assessed using ASTM D1654 [13].

Three scribed test panels of each alloy/pretreatment and actual Bradley components were attached to selected locations on a Family of Medium Tactical Vehicles (FMTV) test vehicle at ATC for exposure to the Munson automotive test track facility [8]. Figures 3 and 4 illustrate the mounting schemes used for test panels and Bradley components. The Munson facility, based upon General

Motor's (GM's) road test, combines vehicle durability tests with accelerated corrosion events to simulate conditions that a fielded Army vehicle would likely encounter (Tables 10–13). The test panels and components were exposed to test track conditions for seven phases that represented seven equivalent years of exposure in a fielded Army environment. Interestingly, seven years corresponds to the overhaul schedule for Bradleys in service but in this case, the seven phases of exposure happened to be the actual exposure time remaining on the FMTV test vehicle. Each phase consisted of 15 driving and corrosion cycles described in Table 14. At several points within each phase, a high-temperature, high-humidity exposure chamber was used to accelerate corrosion conditions following the road tests. As in GM 9540P [5], the corrosiveness of the environment was monitored using standard plain carbon steel mass loss coupons. These coupons were placed at several locations on the vehicle and were used to monitor the corrosion rates from each phase of testing. The coupons allowed testers to adjust the number of humidity chamber exposures during each phase to increase or decrease the severity of the test [9]. Panels and components were assessed during the exposure duration for degradation due to corrosion and loss of adhesion. At the conclusion of the test track exposure, additional laboratory adhesion measurements were performed.

Three unscribed test panels of each alloy/pretreatment and actual Bradley components were attached to selected locations on an actual Bradley test vehicle at Camp Roberts for 94 days. During the 94-day exposure, the vehicles traveled 93 test track and 4000 durability miles. Figure 5 illustrates the mounting location used for test panels on the Bradley test vehicle.

Paint adhesion for both primed and topcoated panels was determined using a wet adhesion test (Method 6301.2 of Federal Test Method Standard No. 141C [15] as specified in MIL-C-81706 [16]). In this test, a standard adhesive tape is used to check adhesion on painted specimens after soaking for 24 hr in deionized water. After soaking, each panel is removed and quickly dried. Two parallel scribes, 1 in apart, are made within the first minute after removal. Tape is uniformly applied across the scribes and then immediately removed. Upon removal, any evidence of paint separation is noted by visual observation of both the panel and the tape. MIL-C-81706 [16] describes adhesion based on a pass or fail system. To receive a "pass" rating, there must be no separation of the paint from the substrate or between layers of the paint. Additionally, a more detailed rating in accordance with ASTM D3359A [6] was used (Table 15).

Dry adhesion measurements were obtained in accordance with ASTM D3359B [6]. This method employs a 6 × 6 grid of perpendicular scribes spaced at 2-mm intervals. Standard tape is uniformly applied over the cross-hatched area and then immediately removed. Once again, upon removal, any evidence of paint separation is noted by visual observation of both the panel and the tape. The rating method for ASTM D3359B [6] is described in detail (Table 16). Dry

adhesion measurements using this method were performed on all of the exposed panels and components in addition to the initial set reserved solely for adhesion purposes.

Pull-off adhesion measurements in accordance with ASTM D4541 [7] were performed on selected laboratory adhesion and exposed panels and components. For the pull-off adhesion test, a loading fixture commonly referred to as a "dolly" is secured normal to the coating surface using an adhesive. The adhesive used for the treated and untreated panels was cyanoacrylate. After allowing the adhesive to cure for 24 hr in laboratory conditions (Table 17), the attached dolly was inserted into the test apparatus. The load applied by the apparatus was gradually increased and monitored on the gauge until a plug of coating was detached. The failure value (in pounds per square inch [psi]) and the failure mode were characterized and recorded. The pull-off test apparatus and dolly configuration are illustrated in Figure 6. Examples of different failure modes obtained from actual panels are provided in Figures 7–9. For the pull-off test, the specimen must be of sufficient minimum thickness to ensure that the coaxial load applied during the removal stage does not distort the substrate material and cause a bulging or "trampolining effect." On thin specimens such as the Al 6061 test panels, the resultant bulge causes the coating to radially peel away outwards from the center instead of uniformly pulling away in pure tension and thus results in significantly lower readings than for identically prepared thick specimens. Of the panels evaluated in the test matrix, only the 5083 aluminum armor test panels at 0.375 in and the 7039 panels at 0.250 in had adequate thickness for valid pull-off test procedures. All of the Bradley components with the exception of the bilge pump cover had sufficient thickness to accommodate the pull-off procedure.

An additional method used to assess post exposure adhesion on the nonscribed Bradley-mounted Al 6061 test panels was the mandrel bend test. The apparatus used was the "conical" type in accordance with ASTM D522 [17] method A. This procedure examined cured coatings of uniform thickness on sheet metal by bending them over a conical mandrel. As in the pull-off test, thickness issues necessitated the exclusion of some specimen substrates. In this test, only the Al 6061 panels (1/16 in) were thin enough to be used for this procedure. The apparatus used for the bending procedure is shown in Figure 10. Immediately after bending, the specimen coatings were visually examined for cracking. The mandrel diameter at which cracking ceased as determined in the plot in Figure 11(a) is taken as the resistance to cracking value. Figure 11(b) illustrates the correction factor for coating thickness. The total elongation of the coating can be calculated using the measurements and the sum of the elongation from the figures as follows:

$$E = e_1 + tc_1,$$

where:

E = total elongation, %;

e_1 = elongation from Figure 11(a), %;

t = thickness, mils, and

c_1 = correction factor from Figure 11(b).

Coating elongation calculations for panels cracked down the entire length were not possible. However, coating/substrate delamination measurements were taken and compared among the specimens.

3. Results

3.1 Salt Fog

Based upon salt fog performance from a previous study [1], the laboratory salt fog panels were exposed for 3000 hr and assigned one of the ASTM D1654 [13] rating codes in Table 7. In addition, the panels were scraped along the full lengths of the scribes to confirm the extent of the creepback damage upon conclusion of the exposure. The creepback ratings at 3000 hr are plotted in Figures 12–14. For Al 5083, corrosion performance was excellent for Brent Oxsilan AL-0500 and Alodine 5200 pretreatments at or near a perfect 10. In contrast, blistering under the paint and loss of adhesion was severe for the Organosilane-pretreated panels (Figure 15). For Al 7039 panels, Organosilane had the best overall performance followed by Alodine 5200. Unfortunately, there was wide scatter among the data for these panels with ratings ranging from 1 to 10. The Brent treatment was consistently low in performance with ratings of 2 across all three panels. For Al 6061 panels, there was a wide disparity between the pretreatment candidates. The Brent process was clearly superior with a perfect 10 or no damage vs. extensive blistering and creepback at 16 mm or further on the Alodine 5200 and Organosilane panels rendering assessments of 0 and 1. Post-exposure dry- and pull-off-adhesion measurements were also performed on the panels, and the results are summarized in sections 3.6 and 3.7.

3.2 Cyclic Corrosion Test Chamber (CCTC) (GM 9540P [5])

The painted panels and components were all subjected to 120 cycles of GM 9540P [5]. The assessment used for 9540P is identical to the assessment for ASTM B117 [4] salt fog for painted specimens (Table 7). The creepback ratings at 120 cycles are plotted in Figures 16–19. As in salt fog, the failure mode for the painted

panels was blistering along the scribe. For Al 5083, most panels sustained the full 120-cycle duration without any damage. An exception was one Organosilane panel rated a 6 which had some blistering along the scribe. As in salt fog, the best performing pretreatments for Al 7039 were Organosilane followed closely by Alodine 5200 with much less scatter among the data and, similarly, the Brent pretreated panels had significantly greater damage. For Al 6061, overall damage was less severe than for salt fog and once again the Brent pretreatment excelled for this alloy. Performance for Brent panels ranged from 8 to 10, Organosilane was next best with scattered ratings ranging from 5 to 10, and Alodine 5200 rated poorest with data ranging from 4 to 5. Headlight guards from actual Bradleys, composed of Al 5083, scribed on three flat surfaces each, were also exposed. For these components, all three pretreatments endured the full 120-cycle duration with no corrosion damage. As in salt fog, post-exposure dry- and pull-off-adhesion measurements were performed on the panels and components, and the results are summarized in sections 3.6 and 3.7.

3.3 ATC Automotive Test Track

Panels and components were all scribed and subjected to seven phases or "equivalent years" of exposure at the ATC test track. As in salt fog and GM 9540P [5], the assessment used for characterization of corrosion damage was ASTM D1654 [13] (Table 7). It became immediately apparent that the test track environment was significantly more severe than the chamber-based methods. Damage measured at just four phases was already severe for several of the test panels (Figure 20). The extent of the damage at four-phases exposure is plotted in Figures 21–23. For the 5083 panels the Brent Oxsilan AL-0500 and Alodine 5200 were undamaged; however, the corrosion damage on the Organosilane-treated panels was severe and consistent across all three panels—one each mounted on the sides and the tailgate—all rating a 4. The 7039 panels also showed significant damage at four-phases but much of it came from delamination problems as was seen in Figure 20. Much of the adhesion problems appeared in the Brent and in the Alodine 5200 panels with two of the Alodines degraded to 5 ratings and one of the Brent panels degraded to a 0. The Organosilane-treated 7039 panels fared well and rated from 8 to 9. The 6061 panels all showed significant blistering from their scribe with Organosilanes rating 3 to 5, Brent Oxsilan AL-0500 rating 3 to 4, and Alodine 5200 rating 1 to 3. Encouragingly, the Bradley taillight guards and bilge pump covers fared better than the panels at four phases with little or no damage. At this point in the test track exposure, selected panels were removed from the test vehicle for review by the Bradley Environmental Management Team.

The remaining panels and components continued exposure to seven test track phases. At the conclusion of seven phases, the remaining panels and components were evaluated and are plotted in Figures 24–27. For the remaining

panels, the relative trends noted among the pretreatments for each alloy remained consistent with the four-phase evaluations. The only noted difference for the panels was the advancement of the blistering and delamination from the scribes. In contrast with the four-phase observations, the Bradley components both exhibited corrosion damage. For the Organosilane-treated Al 5083 taillight guard, the blistering creep was severe and rated a 0. In addition, there was severe chipping and paint loss near the mounting point which was not visible for either of the other two treatments, both of which scored perfect 10 ratings (Figures 28–29). The results for the Al 5083 bilge cover differed in that the Organosilane cover rated best with a 10 followed by Alodine 5200 and Brent which rated 9 and 5, respectively (Figure 30). As in salt fog and GM 9540P [5], post-exposure dry- and pull-off-adhesion measurements were performed on the panels and components, and the results are summarized in sections 3.6 and 3.7.

3.4 Fielded Bradley Vehicle Exposure—Camp Roberts, CA

The panels and components exposed at Camp Roberts upon completion of the durability miles were sent to ARL for examination. None of the panels or components were scribed before exposure; however, panels and components were examined closely for blistering or delamination. While there was some chalking of the 383 green CARC MIL-C-53039 [11] topcoat as a result of ultraviolet exposure from sunlight, none of the panels or components returned exhibited blistering or delamination problems. Once again, as in salt fog, GM 9540P [5], and ATC Test Track post-exposure dry- and pull-off-adhesion measurements were performed on the panels and components and the results are summarized in sections 3.6 and 3.7. In addition, conical mandrel bend tests were performed on the unscribed Al 6061 panels to screen for any gross adhesion deficiencies in any of the three candidates.

3.5 Wet Adhesion

The data from the wet adhesion test, in accordance with ASTM D3359A [6], is illustrated in Figures 31–33. Federal Test Method Standard 141 method 6301 [15] used by the military calls for no intercoat separation whatsoever at the scribe in either wet or dry testing, which corresponds to a 5 rating on the ASTM scale (Table 8). For Al 5083, only Organosilane rated 1 was unable to achieve a 5 rating. In contrast, on Al 7039, Organosilane was the only pretreatment which did rate a 5. Brent and Alodine 5200 rated fair and poor with 2 and 0 ratings, respectively. For Al 6061, performance was excellent with all three candidate pretreatments rating a 5.

3.6 Dry Adhesion

Extensive dry adhesion performance data, in accordance with ASTM D3359B [6], for panels and components both initial, and after various exposure methods is plotted in Figures 34–53. The dry adhesion test, by nature, is more severe than wet adhesion due to the amount of scribes and their close proximity to one another. Due to this severity, a perfect score of 5 is usually more difficult to attain.

For the initial unexposed Al 5083 panels, adhesion was very good with Brent and Organosilane rating a 5 and Alodine 5200 rating a 4. Adhesion problems were found on Al 7039 with Alodine 5200 rating a 0 and Brent rating a 1. However, Organosilane had an excellent rating of a perfect 5. Initial dry adhesion for Al 6061 was good for all three treatments with Alodine 5200 and Brent rating a 4 and Organosilane rating a 5. For the headlight guards, adhesion was good with Organosilane and Brent rating a 4 and Alodine 5200 rating a 5 (Figures 34–37).

For post-3000-hr ASTM B117 [4] salt fog, dry adhesion measurements were performed in unaffected zones away from the scribes. As in initial conditions, adhesion for exposed 5083 panels was excellent with multiple Alodine 5200 and Brent panels all rating a 5. Organosilane-treated 5083 panels also were very good rating 4 to 5. Exposed Al 7039 panels performed similarly to the initial state with major loss of adhesion for both Brent, which rated a 0 for all panels, and Alodine 5200, which rated from 1 to 2. Organosilane-treated 7039 was significantly better with ratings ranging from 3 to 5. Adhesion for salt fog-exposed Al 6061 was good with all Brent- and Alodine 5200-treated panels rating a 5. Al 6061 Organosilane panels ranged from 4 to 5 (Figures 38–40).

For post-120-cycle GM 9540P [5], dry adhesion measurements were performed in unaffected zones away from the scribes. For Al 5083 panels treated with Brent and Alodine 5200 exposed to GM 9540P [5], adhesion was unaffected with all measurements rendering 5 ratings. In contrast, GM 9540P [5] exposed Organosilane-treated Al 5083 panels experienced total loss of adhesion rating a 0 across all three panels. As in the previous tests, adhesion on Al 7039 proved more difficult. Organosilane was best albeit scattered with ratings ranging from 0 to 4. Next best, though poor, was Brent with ratings ranging from 0 to 1. Worst performing was Alodine 5200 which rated a 0 across all panels.

Adhesion ratings for GM 9540P [5] exposed Al 6061 panels were very good with all three treatments rating 4 to 5 across all of their individual panels, respectively. Results for the headlight guards were mixed, but good overall. Best performing was Alodine 5200 with 5 ratings. Next best was Organosilane with ratings ranging from 4 to 5. GM 9540P-exposed headlight guards with Brent ratings ranged from 3 to 4 (Figures 41–44).

For post-seven-phase ATC test track exposure, dry adhesion measurements were performed in unaffected zones away from the scribes. As recorded in GM 9540P [5], for Al 5083 panels treated with Brent and Alodine 5200 and exposed to test track conditions, adhesion was unaffected with all measurements rendering 5 ratings. Similarly, test track-exposed Organosilane-treated Al 5083 panels experienced total loss of adhesion rating a 0 across all panels. Post-test track adhesion for Al 7039 panels was severely degraded across all three treatments. With the exception of one Organosilane-treated panel which rated a 3, all of the exposed panels experienced total coating removal and rated a 0. Post-test track adhesion for all 6061 panels was much better Organosilane and Alodine 5200 rating a 5 and Brent rating a 4. All taillight guards mounted under the wheelwell performed flawlessly in dry adhesion with 5 ratings across all three pretreatments. Dry adhesion ratings for the bilge cover were also very good with the Brent- and Organosilane-treated covers rating a 5 and those Alodine 5200-treated rating a 4 (Figures 45–49).

For post-durability exposure at Camp Roberts, dry adhesion measurements for panels and components were performed in unaffected zones free from chips or abrasions. Adhesion for all three pretreatments was very good ranging from 4 to 5 for all panels. As expected, adhesion problems occurred for Al 7039 panels. Organosilane was best with ratings ranging from 2 to 3. Brent and Alodine 5200-treated panels rated worst with scattered ratings weighted toward the low end of the 0 to 3 range. Adhesion for Al 6061 panels was very good for all three pretreatments ranging from 4 to 5. Adhesion for the pretreated Bradley components was very good for all treatments rating 4 to 5 except for Organosilane on a headlight guard which rated fair at a 3 (Figures 50–53).

3.7 Pull-Off Adhesion (ASTM D4541 [7])

As an alternative to tape-based methods, pull-off tests using hydraulic methods ASTM D4541 [7] were initiated to confirm measurements obtained in dry adhesion conditions. The individual readings and failure conditions are tabulated in Tables 18–22. Measurements were taken from all panels and components except Al 6061 panels which were too thin to yield valid data.

For initial unexposed conditions, all of the pretreatments had excellent adhesion in excess of 3000 psi on Al 5083. For Al 7039, Brent and Alodine 5200 pretreatments had poor adhesion as a result of delamination between substrate and primer with readings of 520 psi and 630 psi, respectively. As in dry adhesion methods, Organosilane was the only pretreatment to which paint adhered on 7039 with a measurement of 2620 psi.

For post-3000-hr ASTM B117 [4] salt fog, pull-off adhesion measurements were performed with the test dollies glued to panels in unaffected zones away from the scribes and dry adhesion areas. As in initial conditions, adhesion was very

good for all pretreatments on Al 5083 with all failure modes as interlayer between the primer and the topcoat. As in results obtained from Al 7039 in initial conditions, only Organosilane had complete adhesion of the paint to the substrate with adhesion >2100 psi. Alodine 5200 and Brent pretreatments failed adhesion with substrate separation from the paint at 700 psi and 520 psi, respectively.

For post-120-cycle GM 9540P [5], pull-off adhesion measurements were performed with the test dollies glued to panels and components in unaffected zones away from the scribes and dry adhesion areas. As in previous measurements, adhesion tensions were excellent for all three pretreatments. The failure modes were interlayer except for Organosilane which was substrate at 2190 psi. In a departure from previous measurements on Al 7039, the Brent-pretreatment adhesion was highest with tension >2500 psi and interlayer failure between topcoat and primer. Organosilane, as in previous measurements, performed well on Al 7039 with a tension of 1950 psi with a mixed substrate/interlayer failure mode noted. Adhesion on the Al 5083 headlight guard components was excellent for all three pretreatments with tensions ranging from 2320 to 2520 psi and all failures at coating interlayers.

For post-seven-phase ATC test track, pull-off adhesion measurements were performed with the test dollies glued to panels and components in unaffected zones away from the scribes and dry adhesion areas. For Al 5083 panels, adhesion was excellent for Brent and Alodine 5200 pretreatments with tensions ranging from 2100 to 2700 psi with all failure modes mixed except for one Alodine 5200 at 2700 psi which failed via substrate. For Al 7039, as in previous measurements, adhesion values for all pretreatments were reduced vs. values for Al 5083. The readings as a whole for the test track-exposed Al 7039 panels ranged from 540 to 2100 psi. The failure mode for all pretreatments was substrate or substrate/interlayer. As in previous measurements, adhesion was excellent for taillight guards with tensions ranging from 2120 to 2490 psi with coating interlayer failure mode for all three pretreatments.

For post-4000-mi durability testing at Camp Roberts, pull-off adhesion measurements were performed with the test dollies glued to panels and components in unaffected zones away from chips and abrasions introduced by the exposure. For Al 5083 panels, adhesion, as in previous measurements, was very good ranging from 2090 to 3030 psi with three readings each per pretreatment. Interlayer separation between primer and topcoat was the dominant failure mode except for one Alodine 5200 and Organosilane with substrate/interlayer hybrid failure. On Al 7039, adhesion for Organosilane was most consistent ranging from 2270 to 2410 psi. The failure mode for the Organosilane for two of the three panels was hybrid interlayer/substrate and interlayer for the remaining panel. For Brent, two of the three panels exhibited substrate failures at 560 and 570 psi with one panel performing well with

2470 psi and primer/topcoat interlayer failure. The mixed Bradley components (two headlight guards, two taillight guards, and one headlight bracket), as in all other adhesion measurements, performed well. Pull-off tensions ranged from 2310 to >3500 psi with all failing via interlayer separation between the primer and the topcoat.

3.8 Conical Mandrel Bend (ASTM D522 [17])

An additional method used to assess the adhesion characteristics for unscribed, thin Al 6061 panels returned from durability exposure at Camp Roberts, was the conical mandrel bend test. While the number of specimens was limited, the test was mainly performed for screening purposes as a means of detecting any gross degradations in adhesion for any of the three candidate pretreatments. The results tabulated in Table 20 showed complete cracking across the entire length of two of three Brent-treated panels and the one remaining Alodine 5200 panel. One of three of the Organosilane-pretreated panels showed cracking down the entire panel length. Elongation measurements were only possible for the panels which did not crack completely. Although enough elongation calculations were not possible for meaningful comparison of the pretreatments on Al 6061, delamination distances from the small end of the cone were compared between the treatments. From the delaminations measured, evidence of smaller delamination distances and two panels not entirely cracking, indicated that Organosilane-treated panels perhaps performed better than the others. However, it must be stated that no large scale delaminations occurred on any of the 6061 panels as a result of the mandrel bends.

4. Discussion

The intent of this study was to provide as much detailed performance based information as possible on three final candidate nonchromate conversion coatings. The ultimate goal of this study and the additional economic studies performed by Concurrent Technologies Corporation is to determine the best replacement for hexavalent chromium based Alodine 1200 currently in use by the original equipment manufacturers (OEMs) and depots. Previous work determining the three final candidates focused mainly on corrosion performance and screening to reject the lesser alternatives. In this study, once again accelerated corrosion chamber methods were used; however, additional emphasis was placed on more realistic conditions such as the ATC Automotive Test Track Munson facility and fielded durability conditions at Camp Roberts. Greater emphasis was placed on coating adhesion with a much more comprehensive approach taken including additional methods of evaluation such as pull-off and mandrel bend as well as supplementary adhesion measurements

taken *after* exposure to determine whether exposure to harsh conditions altered the performance of the conversion coating. Another key aspect was the inclusion of actual Bradley components that were surface prepared, pretreated, and coated, under supervisory guidance by the pretreatment vendors, and professionals from OEMs such as Concurrent Technologies and United Defense Limited Partnership.

As in previous work, salt fog was used as a means of determining corrosion resistance. The three final candidates, Organosilane, Brent, and Alodine 5200, had been among the best performers overall in the previous study and correspondingly were exposed for a significantly longer duration for this study. For Al 5083, the salt fog performance for Alodine 5200 and Brent pretreatments was excellent with very little or no damage. However, the Organosilane showed considerable damage due to blistering outwards from the scribe. Considering that over 80–90% of the aluminum in fielded Bradleys is Al 5083, it is extremely important for a conversion coating to perform on this alloy. For Aluminum 7039, the results were almost opposite to Al 5083 with Organosilane performing better than Alodine 5200 and much better than Brent. Reasons for the apparent discrepancy with Organosilane on Al 7039 were discussed at a previous Bradley EMT meeting. Key elements from the EMT discussion were:

- The Al 7039 test panel material had been stored outdoors without adequate overhead cover at Aberdeen Proving Ground and was heavily oxidized.
- It was determined from discussion with the surface preparers, that an additional Oakite 360L alkaline etch step is included in the surface preparation phase for Organosilane. This etch step, not present in either of the two other pretreatments, was likely key to removing excess oxides and preparing a good surface to which primer could adhere (Table 4).

For Al 6061, the Brent pretreatment was clearly superior at 3000 hr.

For greater correlation with actual outdoor field environments encountered in service life, the 120-cycle GM 9540P [5] cyclic corrosion test was used. For Al 5083, all three pretreatments performed flawlessly except for one of the Organosilane-treated panels that showed some blistering from the scribe. Once again as in salt fog, Organosilane performed better than Alodine 5200 and significantly better than Brent on Al 7039 likely due to reasons previously discussed. For Al 6061, Brent was once again the best performer, followed by Organosilane, then Alodine 5200 in corrosion resistance. For the Bradley headlight guards, corrosion resistance was excellent for all three candidates with no discernable damage after 120 cycles. The outstanding performance of the pretreatments on the components was likely due to the grit-blasted surface preparation and the subsequent thicker coatings applied to overcome the greater surface profile variations inherent from the surface-blasted condition.

To provide as realistic a field environment as possible (yet significantly compress the time to achieve significant corrosion damage), test panels and components were attached to an FMTV test vehicle provided courtesy of PM FMTV at the ATC Munson test track and exposed for seven phases. It became readily apparent from observations at just four phases that the degree of corrosion acceleration for the test track was greater than 120 cycles of GM 9540P [5]. The blistering damage for Organosilane on Al 5083 was severe vs. Brent or Alodine 5200 treatments which were not affected throughout the full seven phases. The extent of the corrosion produced on the Organosilane-treated Al 5083, an alloy with very good corrosion resistance in just four phases of test track was problematic. For Al 7039, the trend for salt fog and GM 9540P [5] held true, though less pronounced. Seven full phases were required for the Organosilane to truly exceed Alodine 5200 and Brent in corrosion performance. The improvement was once again likely produced as an effect of the extra alkali etch surface preparation. For aluminum 6061 all treatments had significant corrosion damage from blistering; however, Alodine 5200 had slightly more corrosion damage at four phases and subsequently at seven phases than the other two treatments. The Al 5083 Bradley components were removed and evaluated upon completion of seven phases. As for the 5083 panels, the Organosilane-treated taillight guard had severe corrosion from blistering from the scribes. In addition, there was significant paint exfoliation and cracking from the vicinity of component anchoring points to the vehicle which was not present on corresponding locations from either of the two other treatments. For the Al 5083 panels and the components, and for Al 5083, the Brent and Alodine pretreatments performed well and would both likely perform well as adequate substitutes for Alodine 1200 given the inherent corrosion resistance of Al 5083.

For additional evaluations, panels and components were exposed on actual fielded Bradley vehicles for 4000 mi at Camp Roberts. Unfortunately, none of the panels were scribed and the exposure time was neither long or severe enough to produce any corrosion on either the panels or components. However, the panels and the components did provide additional adhesion data for dry, pull-off and mandrel bend conditions.

A key requirement for conversion coatings is *an effective surface for adhesion of primer coats*. When an aluminum alloy with good corrosion properties is chosen for a task, adhesion characteristics become the most important factor for choosing the right conversion coating. In the case of aluminum armor alloy 5083 which had an exposed and established mill finish, both Alodine 5200 and Brent pretreatments performed well in wet and dry adhesion on initial unexposed panels and unexposed grit-blast surfaced components. As in the corrosion tests, problems were present for Organosilane-treated panels. For exposed Al 5083 panels and components, both Alodine 5200 and Brent again performed very well with perfect 5 ratings for virtually every exposure with only a few odd

exceptions. The most notable exception was the Brent-treated GM 9540P [5] exposed taillight guards which exhibited reduced adhesion ranging from 3 to 4. In pull-off adhesion, Brent and Alodine 5200 pretreatments performed very well with the majority of the tensions well in excess of 2000 psi and interlayer failure between the primer and the topcoats for all Al 5083 panels and components. Organosilane-pretreated panels tended to fail at lower tensions and more frequently delaminated via the substrate/primer interface indicating reduced adhesion capacity vs. the other pretreatments. For Al 7039, overall adhesion of all pretreatments across all methods was reduced vs. the other alloys. Of the three candidates, Organosilane was clearly the best performing of the treatments across all adhesion test methods. The extent of the performance advantage of Organosilane pretreatment in adhesion was similar to the advantage in corrosion and was likely again due to the initial surface preparation before the pretreatment was applied. Adhesion on Al 6061 appeared roughly equal across all panels and test methods. For the dry adhesion methods, most of the ratings were a perfect 5 with occasional 4 ratings but no clear advantage or disadvantage for any of the pretreatments. Conical mandrel bend tests leaned slightly in favor of Organosilane but the limited extent of the 6061 panels returned from Camp Roberts made definitive ruling on the best adhering pretreatment impossible. However, the mandrel bend test did indicate that no major adhesion deficiencies were present with respect to any treatments on Al 6061.

In this study, all three alloys examined could be characterized by relatively good corrosion resistance relative to the more active aluminum 2XXX series alloys. As a result, coating adhesion became the dominant factor in this study for assessing conversion coating performance. The results for aluminum alloys 7039 and 6061, while interesting, represent a small percentage of actual aluminum material used for the Bradley. Although some Al 7039 armor exists in older Bradley Infantry Fighting vehicles, aluminum 5083 makes up the overwhelming majority of Bradleys as well as other tactical vehicles utilizing aluminum armor. The excellent performance of two conversion coatings, Alodine 5200 and Brent, especially on the actual components of Al 5083 can be interpreted as extremely positive. Either one of these treatments would likely be a successful replacement for hexavalent chromium-based Alodine 1200. The Organosilane conversion coating while more successful on Al 7039, was clearly deficient on Al 5083, almost to the point of appearing to cause corrosion and adhesion problems.

5. Conclusions

(1) Alodine 5200 and Brent Oxsilan AL-0500 showed good corrosion and adhesion performance on aluminum alloy 5083, the alloy of most significance to the current application.

(2) The Organosilane conversion coating showed significantly reduced adhesion strength (ASTM D3359 [6], ASTM D4541 [7]) as well as poor corrosion resistance (ASTM B117 [4], ATC Test Track) vs. the other pretreatments on Al 5083.

(3) The other alloys examined—Al 7039 and Al 6061—showed mixed results. Organosilane performed best on Al 7039. Alodine 5200 performed moderately better than Brent Oxsilan AL-0500 in adhesion and corrosion on Al 7039 in ASTM D4541 [7] pull-off adhesion, and ATC Test Track observations. For Al 6061, ASTM D3359 [6] wet- and dry-adhesion strength was comparable for all three pretreatments. Brent Oxsilan AL-0500 pretreatment showed markedly superior corrosion resistance on Al 6061 in ASTM B117 [4] salt fog.

(4) Considering the overwhelming importance of Al 5083 to the Bradley Fighting Vehicle, either Alodine 5200 or Brent Oxsilan AL-0500 should be considered for implementation since they both showed excellent performance for that particular alloy. Therefore, the selection should be based upon their relative performance on other alloys and economic/environmental factors.

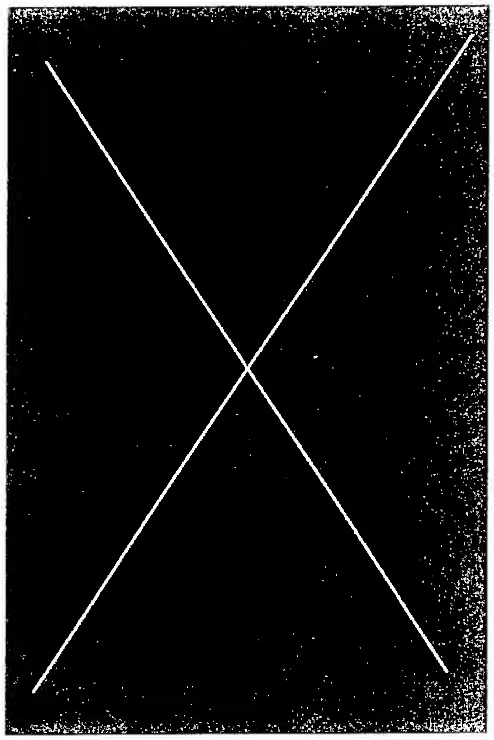


Figure 1. Corrosion test panel initial scribed appearance.

Figure 2. CCTC used for GM 9540P [5].

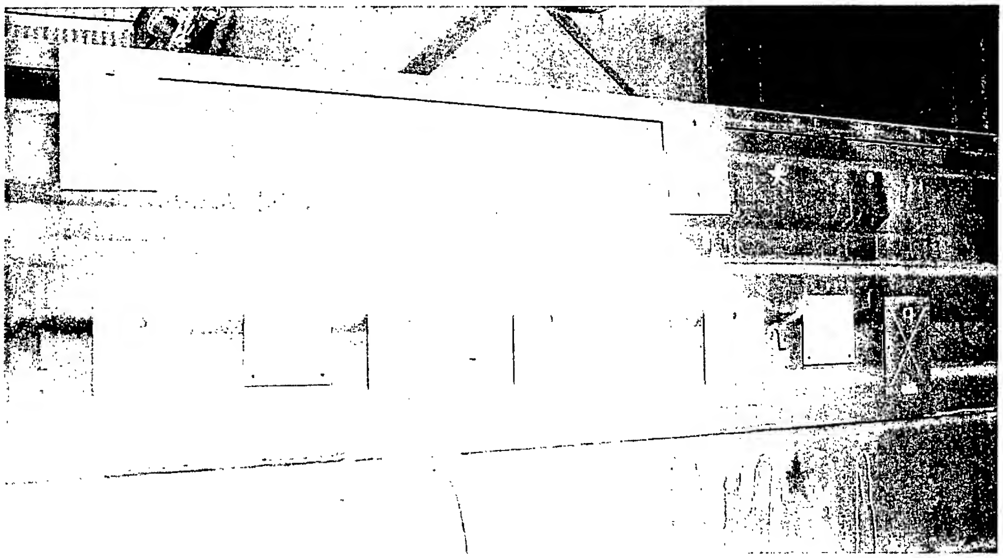


Figure 3. Test panels mounted on FMTV test vehicle tailgate at ATC.

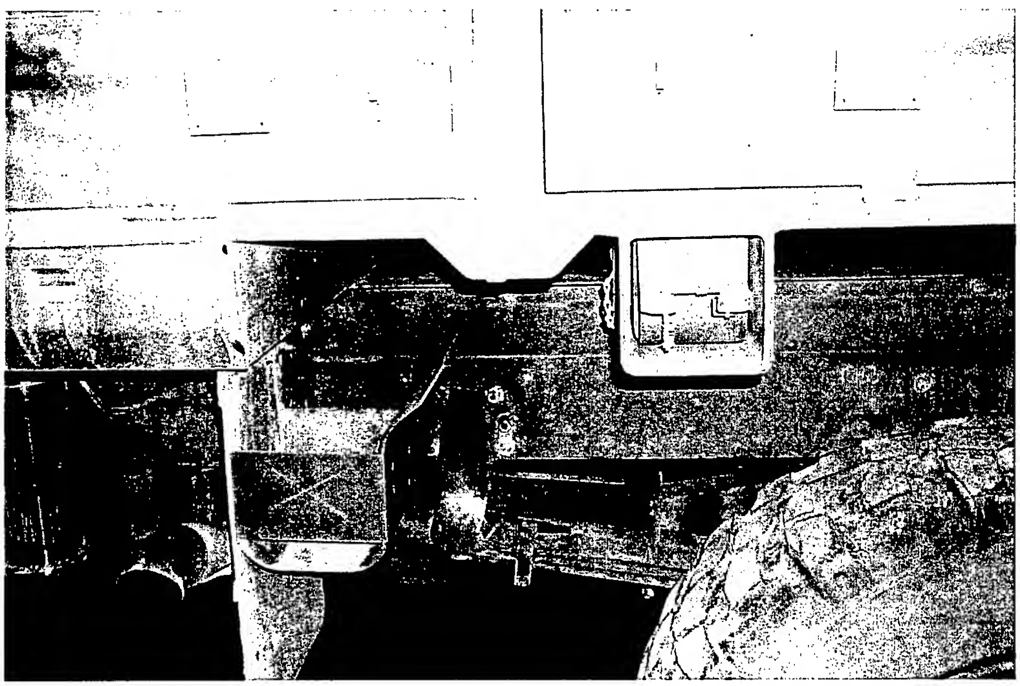


Figure 4. Bradley taillight guards mounted on FMTV test vehicle mudflap bracket near rear tire at ATC.

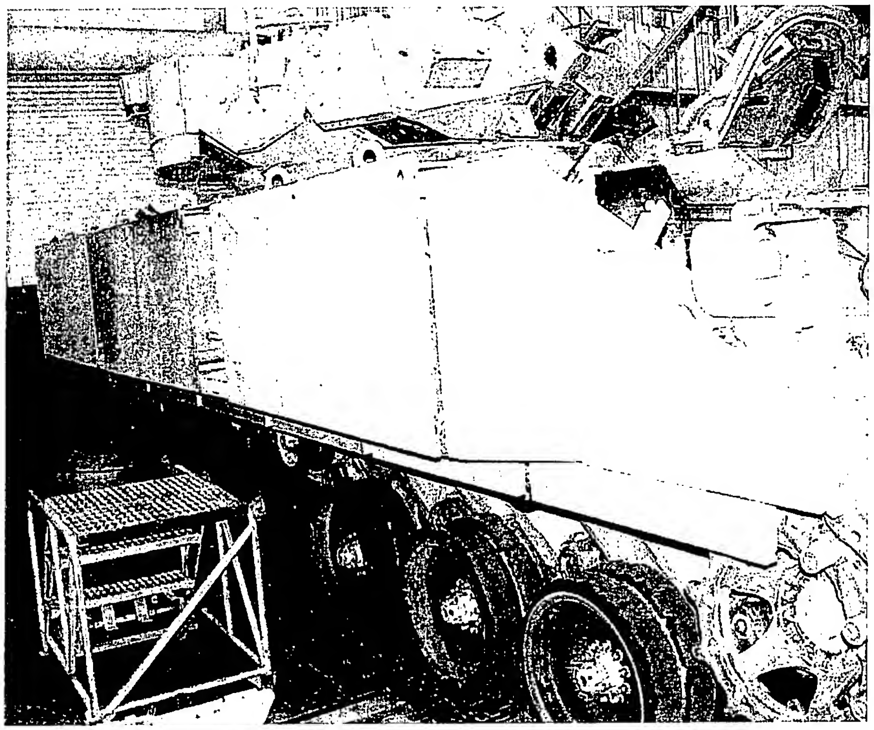


Figure 5. Test panels and headlight guard mounted to Bradley test vehicle at Camp Roberts, CA.

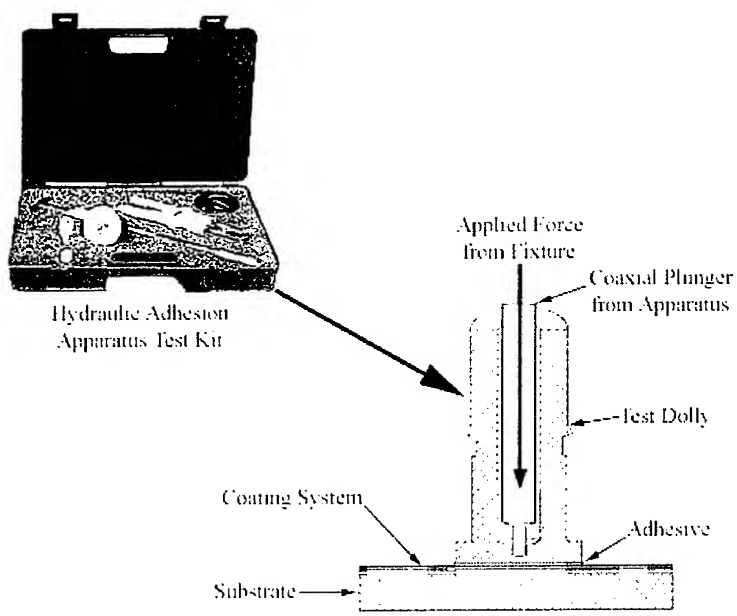


Figure 6. Pull-off hydraulic adhesion test (ASTM D4541 [7]).

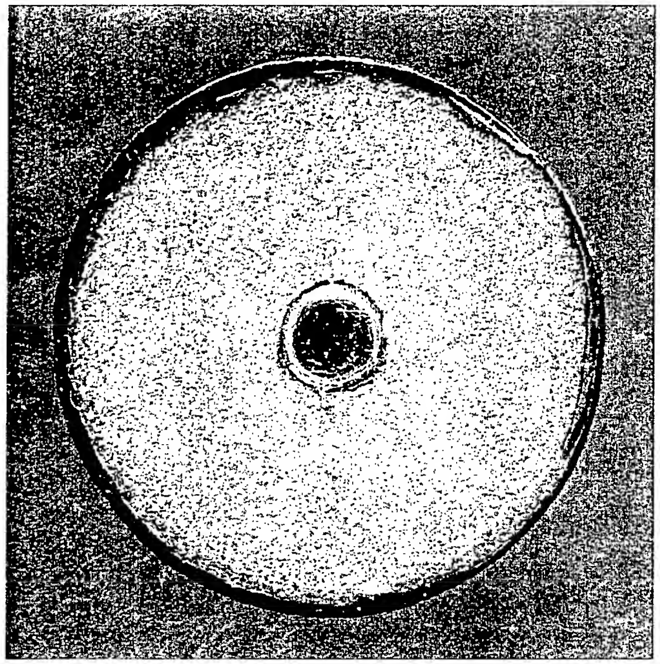


Figure 7. Pull-off adhesion test interlayer failure on Organosilane-treated Al 5083 after exposure at Camp Roberts, CA (2960 psi) (2× magnification).

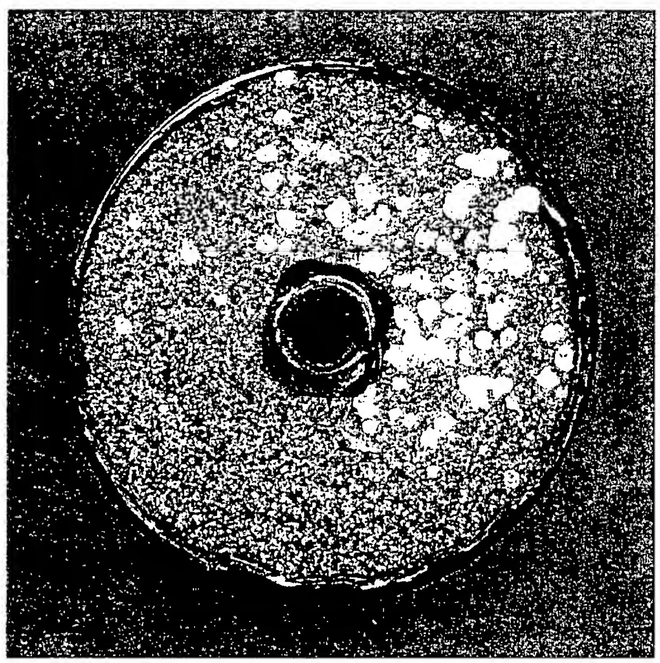


Figure 8. Pull-off adhesion test interlayer/substrate failure on Organosilane-treated Al 7039 after exposure at Camp Roberts, CA (2270 psi) (2× magnification).

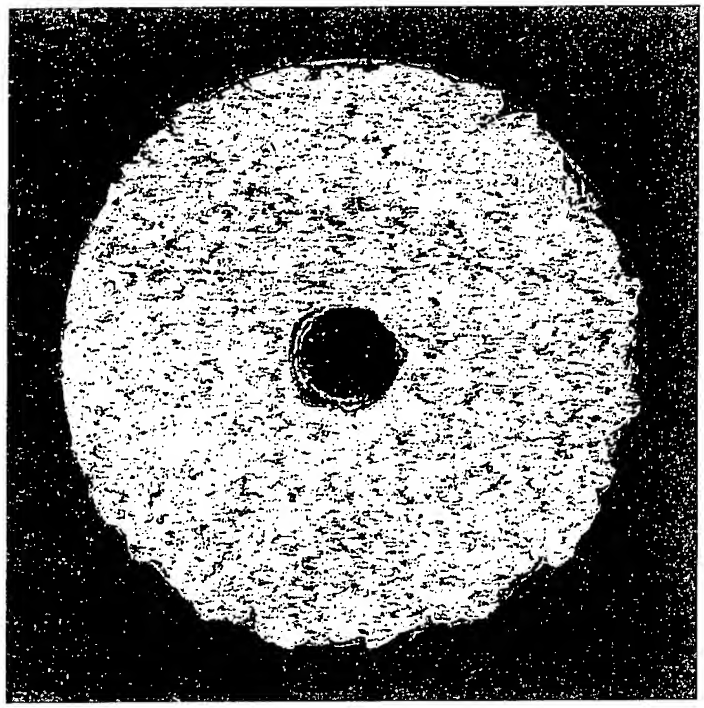
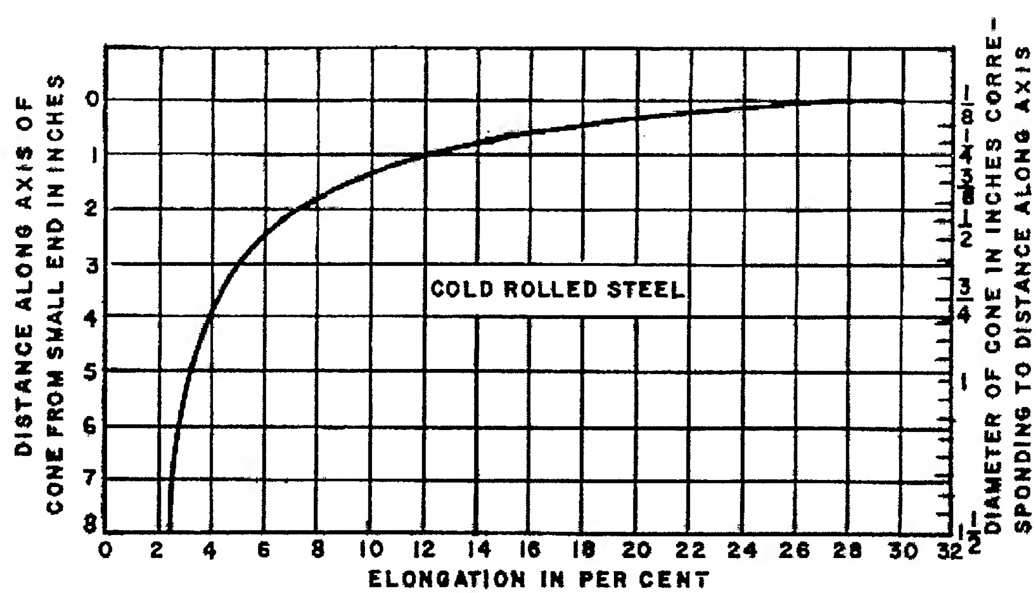
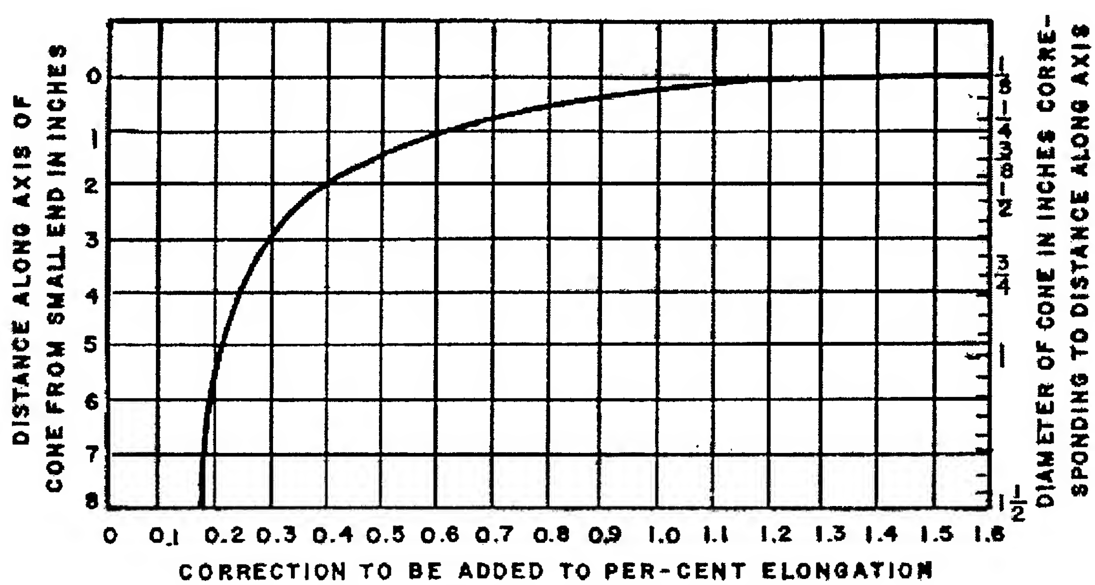


Figure 9. Pull-off adhesion test substrate failure on Brent-treated Al 7039 after exposure at Camp Roberts, CA (570 psi) (2× magnification).

Figure 10. Conical mandrel bend test apparatus.



(a) Determination of coating elongation.



(b) Correction per mil of coating thickness.

Figure 11. Conical mandrel bend test (ASTM D522 [17]).

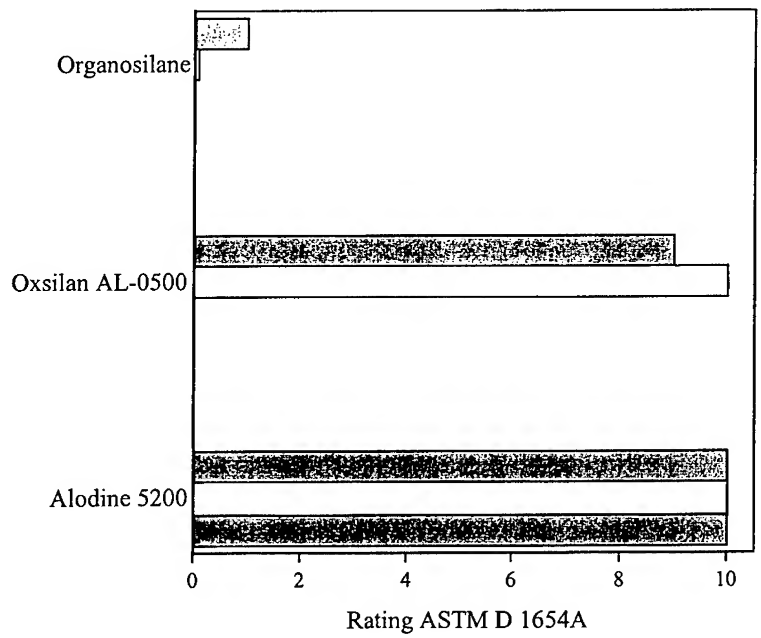


Figure 12. Salt fog performance on scribed CARC-coated Al 5083 panels at 3000 hr (greater is better).

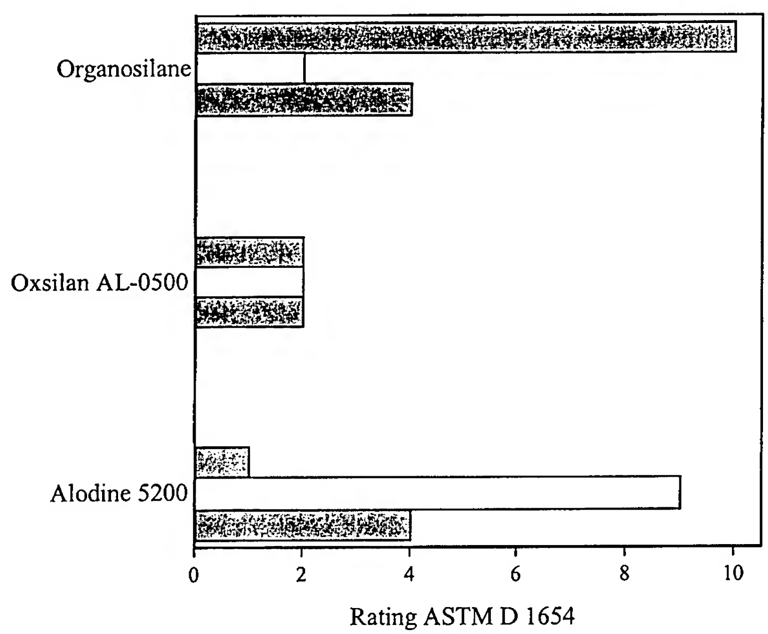


Figure 13. Salt fog performance on scribed CARC-coated Al 7039 panels at 3000 hr (greater is better).

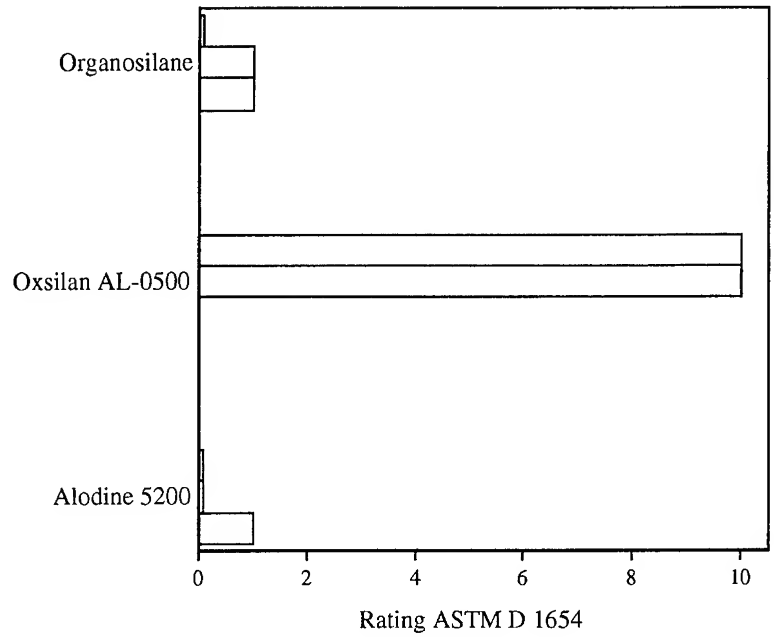


Figure 14. Salt fog performance on scribed CARC-coated Al 6061 panels at 3000 hr (greater is better)

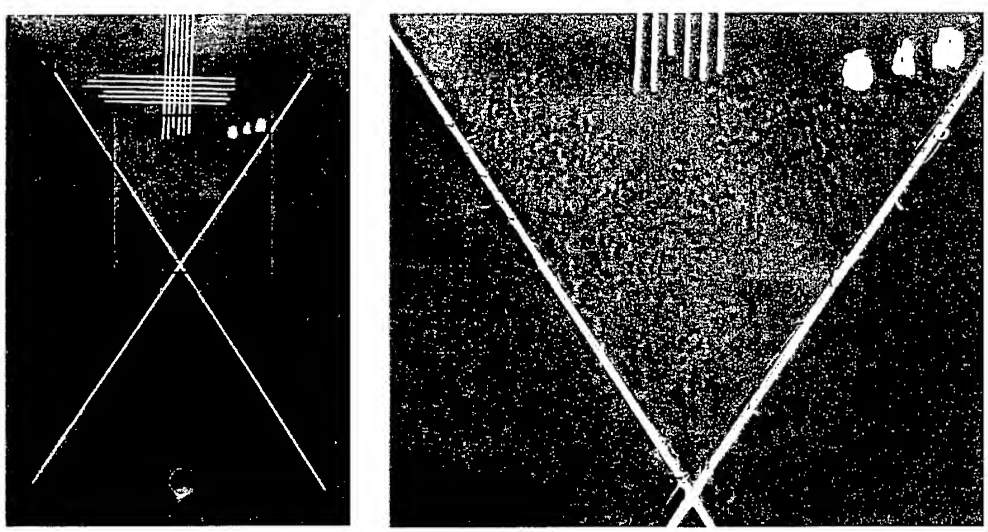


Figure 15. Corrosion damage on Organosilane-treated scribed CARC-coated AL 5083 panels at 3000 hr.

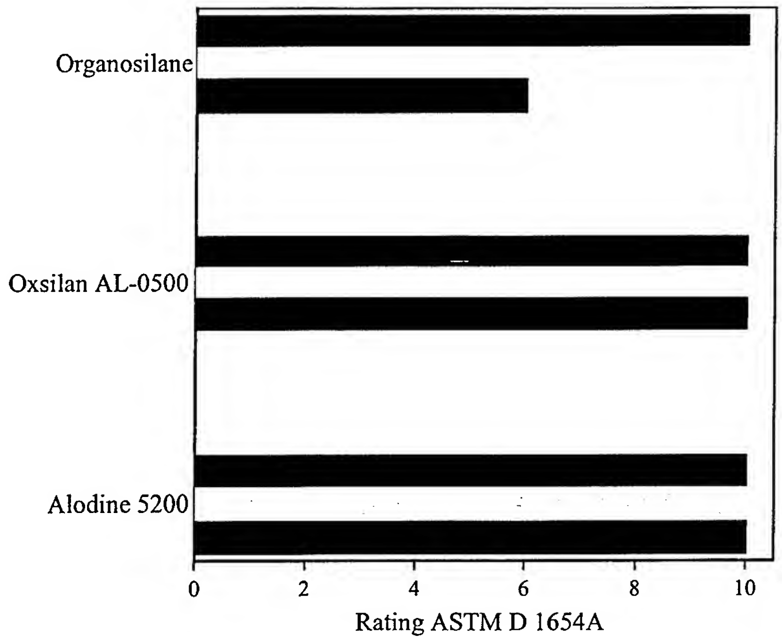


Figure 16. GM 9540P [5] performance on scribed CARC-coated Al 5083 panels at 120 cycles (greater is better).

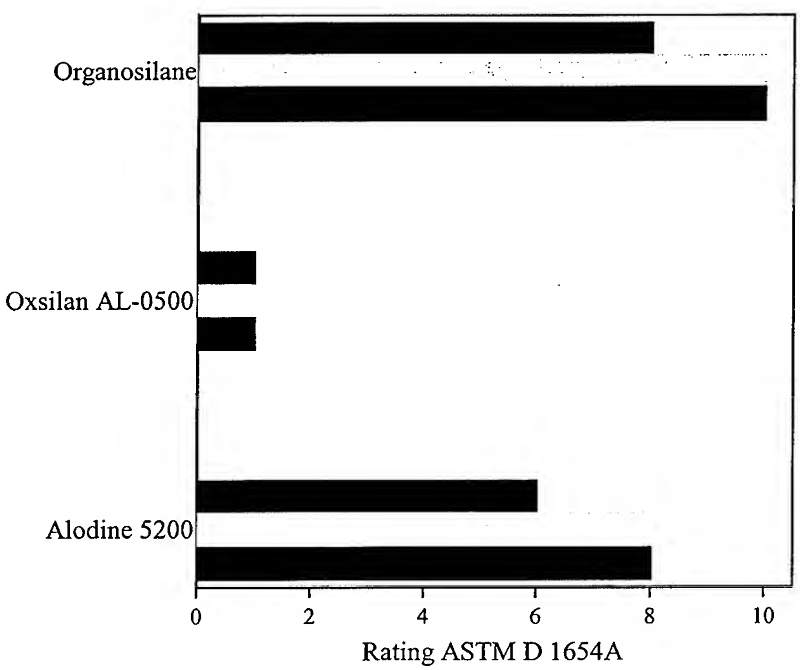


Figure 17. GM 9540P [5] performance on scribed CARC-coated Al 7039 panels at 120 cycles (greater is better).

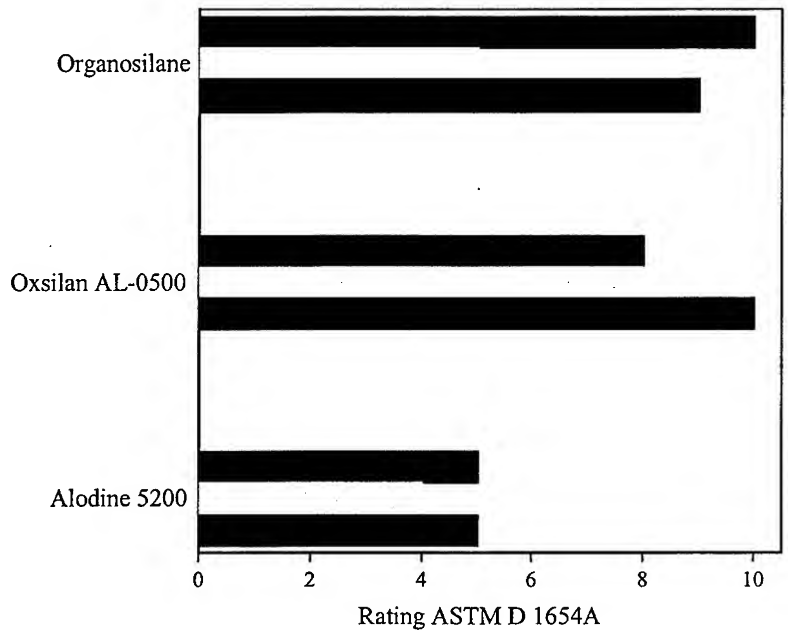


Figure 18. GM 9540P [5] performance on scribed CARC-coated Al 6061 panels at 120 cycles (greater is better).

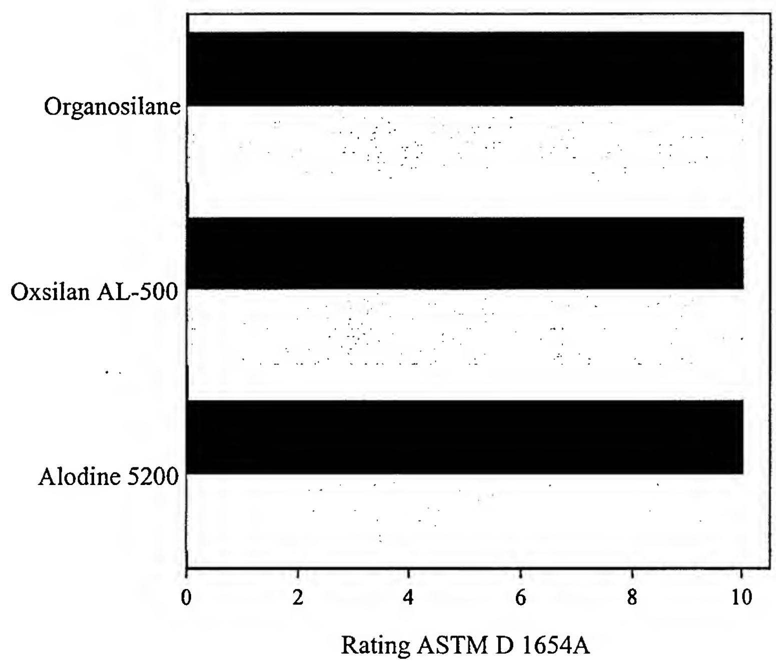
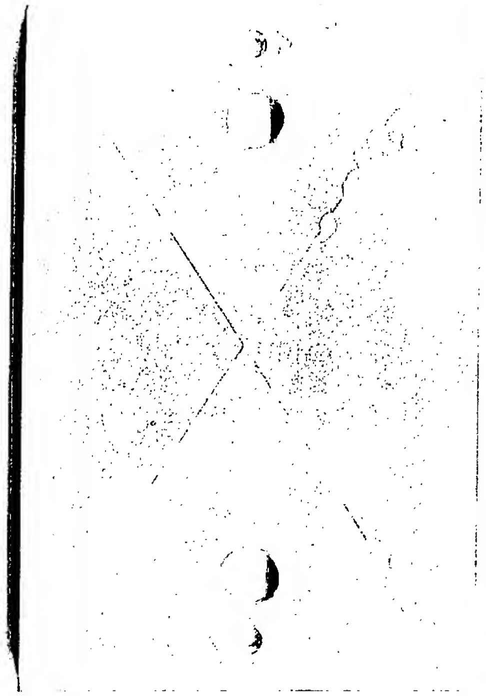
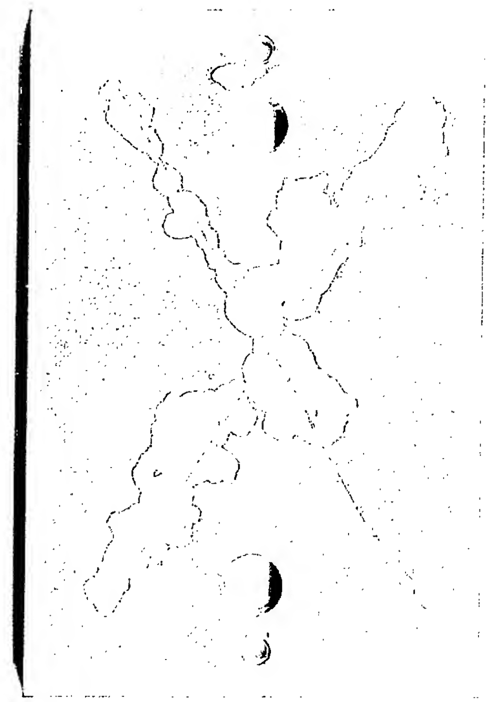


Figure 19. GM 9540P [5] corrosion performance on CARC-coated Al 5083 headlight guards at 120 cycles (greater is better).



(a)



(b)

Figure 20. Corrosion/delamination damage of (a) Alodine 5200 vs. (b) Brent on Al 7039 at four-phases ATC test track exposure.

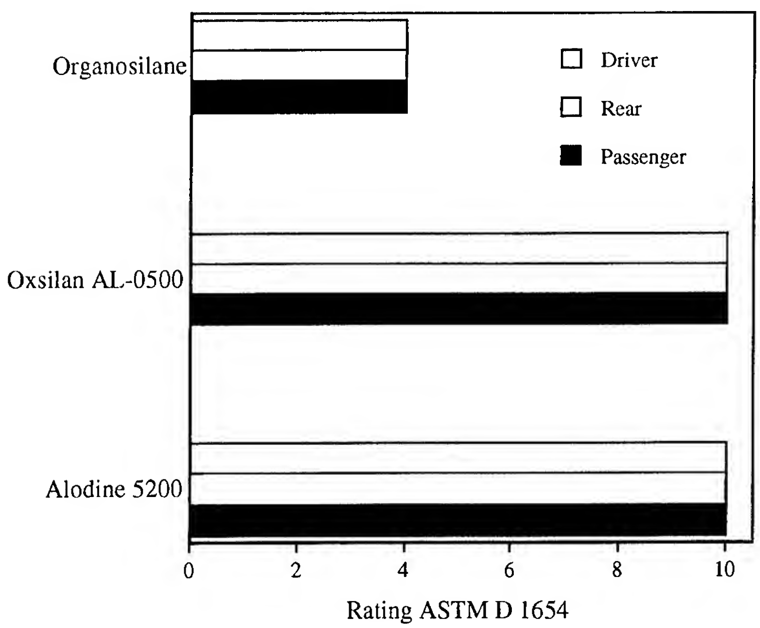


Figure 21. Corrosion/delamination damage on scribed CARC-coated Al 5083 panels at four-phases ATC test track exposure (greater is better).

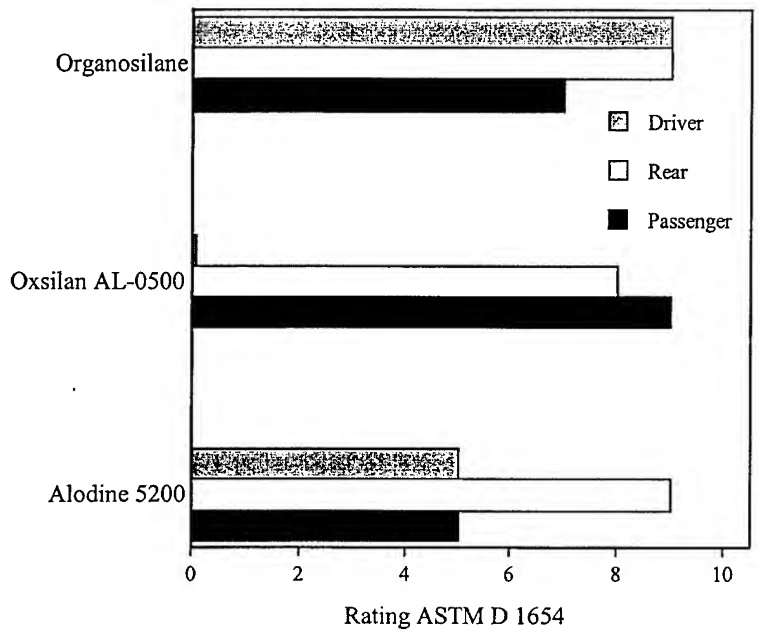


Figure 22. Corrosion/delamination damage on scribed CARC-coated Al 7039 panels at four-phases ATC test track exposure (greater is better).

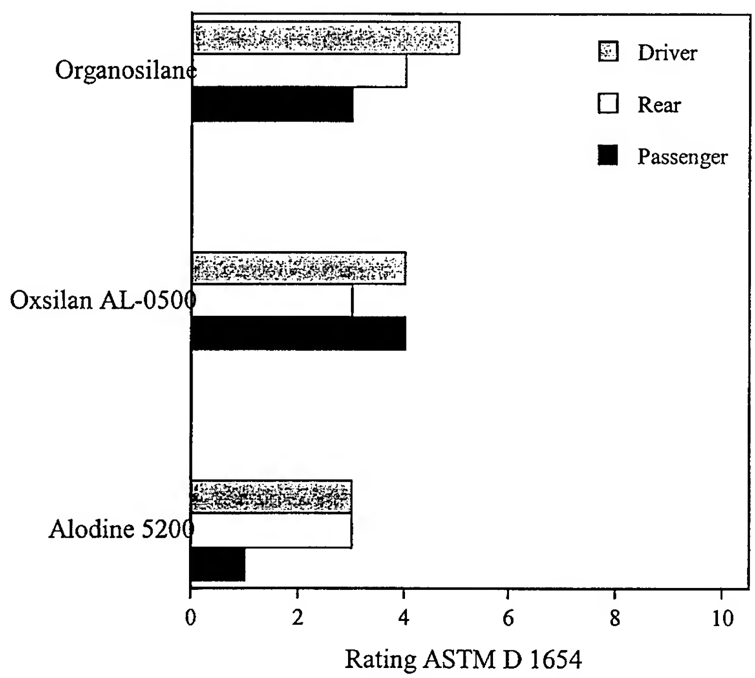


Figure 23. Corrosion/delamination damage on scribed CARC-coated Al 6061 panels at four-phases ATC test track exposure (greater is better).

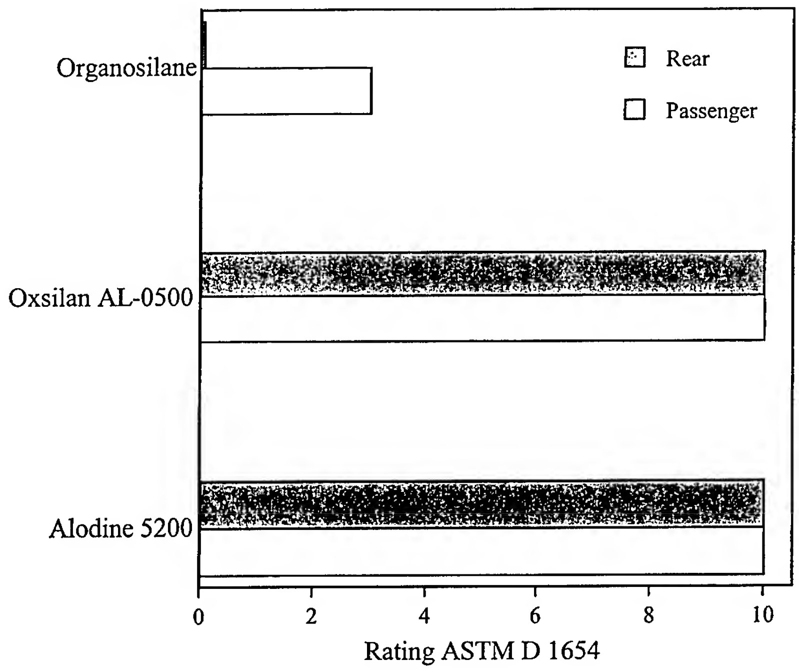


Figure 24. Corrosion/delamination damage on scribed CARC-coated Al 5083 panels at seven-phases ATC test track exposure (greater is better).

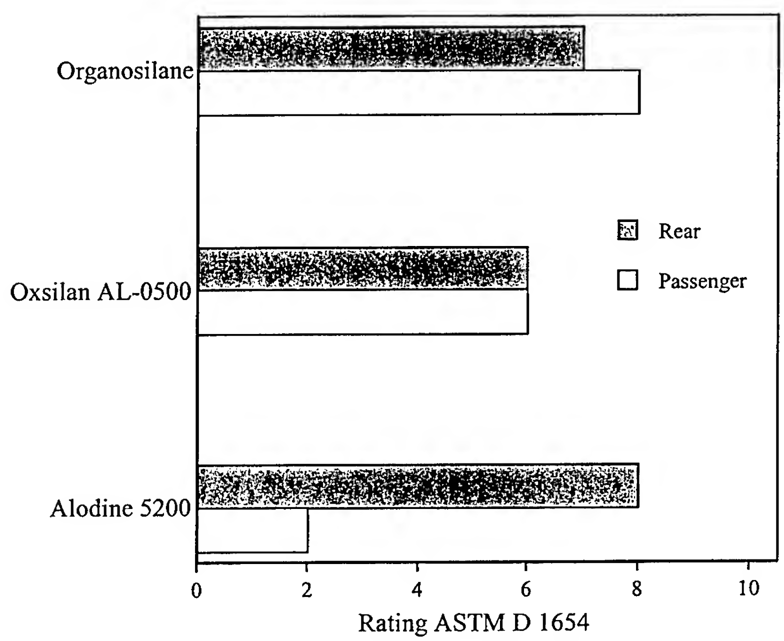


Figure 25. Corrosion/delamination damage on scribed CARC-coated Al 7039 panels at seven-phases ATC test track exposure (greater is better).

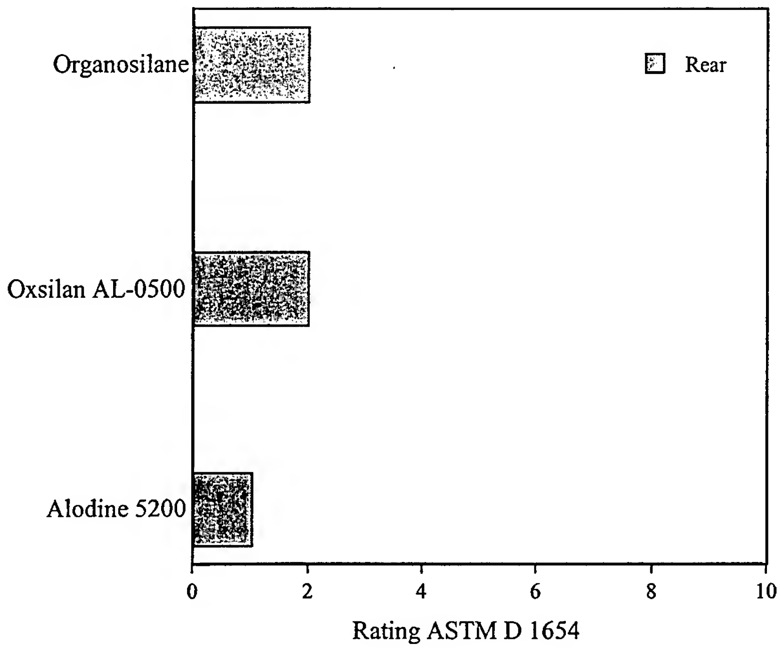


Figure 26. Corrosion/delamination damage on scribed CARC-coated Al 6061 panels at seven-phases ATC test track exposure (greater is better).

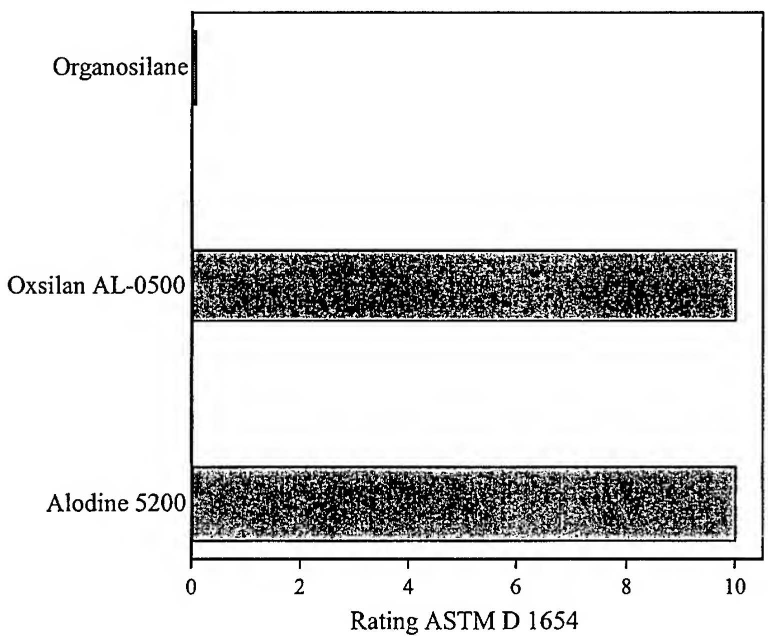


Figure 27. Corrosion/delamination damage on CARC-coated Al 5083 taillight guards at seven-phases ATC test track exposure (greater is better).

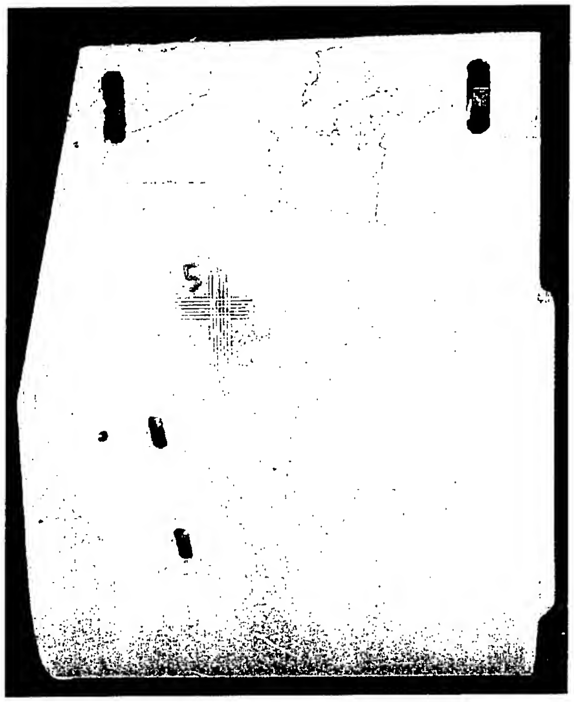


Figure 28. Corrosion/delamination damage on Organosilane-pretreated Al 5083 taillight guard at seven-phases ATC test track exposure.

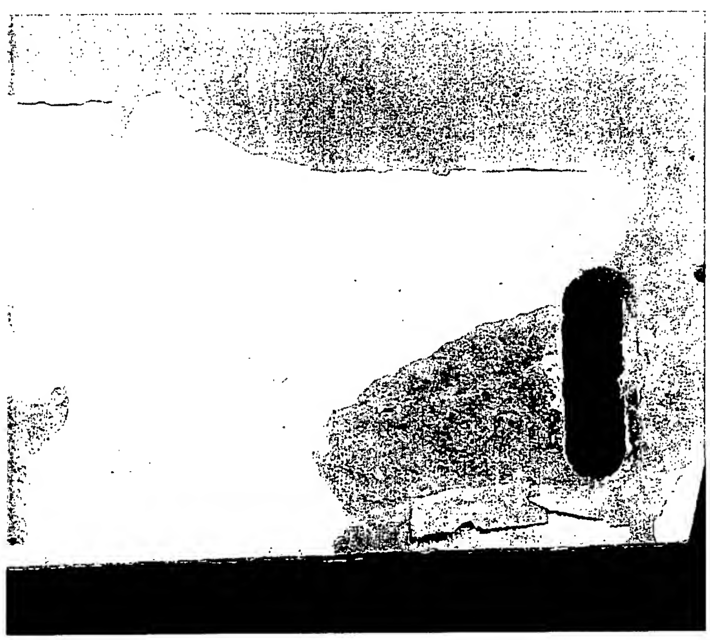


Figure 29. Corrosion/delamination damage (actual size) on Organosilane-pretreated Al 5083 taillight guard at seven-phases ATC test track exposure.

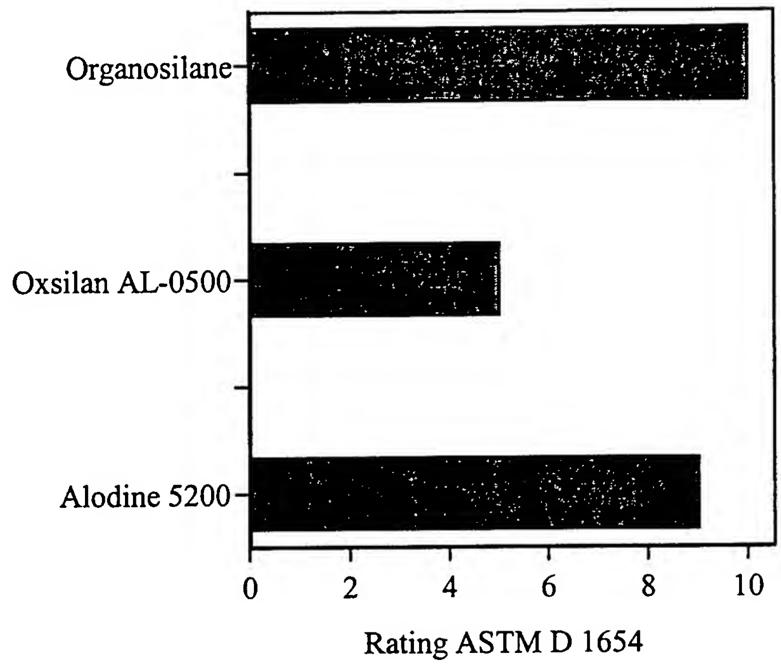


Figure 30. Corrosion/delamination damage on seafoam green-coated Al 5083 bilge cover at seven-phases ATC test track exposure (greater is better).

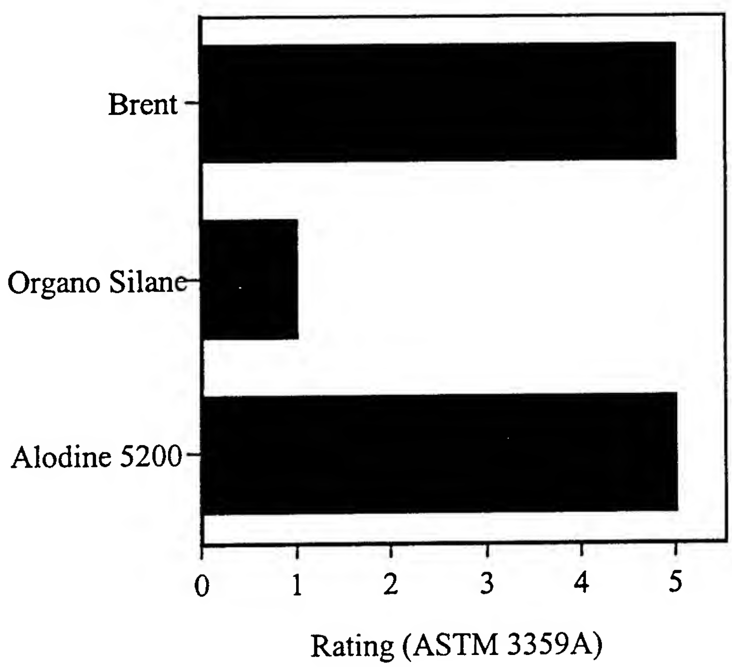


Figure 31. Wet adhesion ratings for aluminum 5083 panels (greater is better).

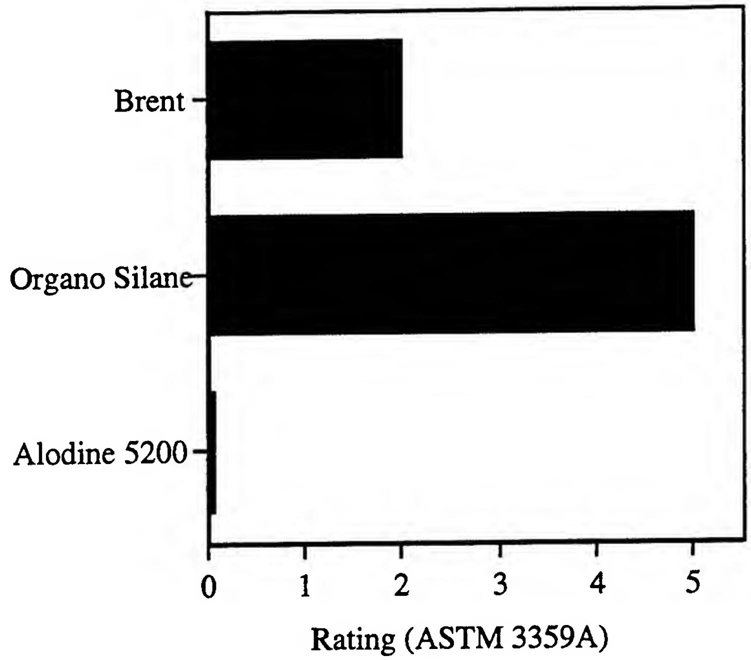


Figure 32. Wet adhesion ratings for aluminum 7039 panels (greater is better).

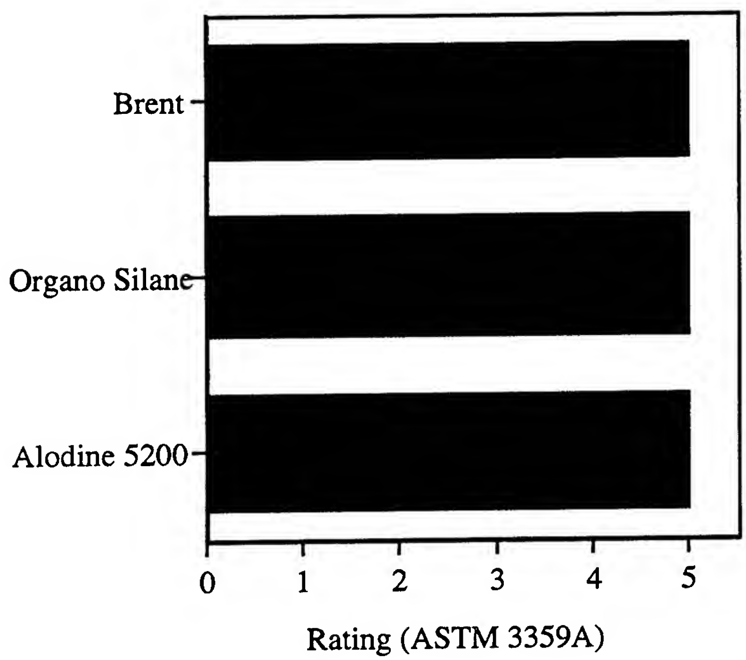


Figure 33. Wet adhesion ratings for aluminum 6061 panels (greater is better).

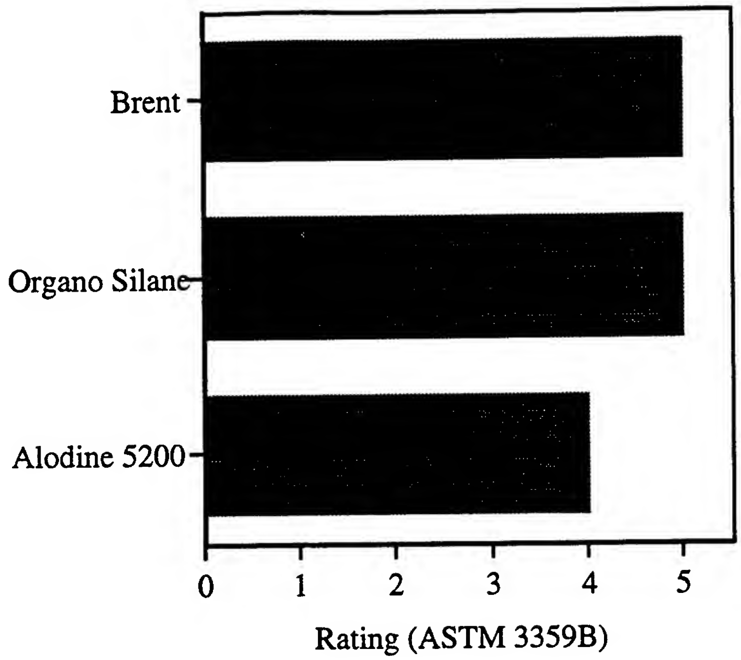


Figure 34. Dry adhesion ratings for unexposed aluminum 5083 panels (greater is better).

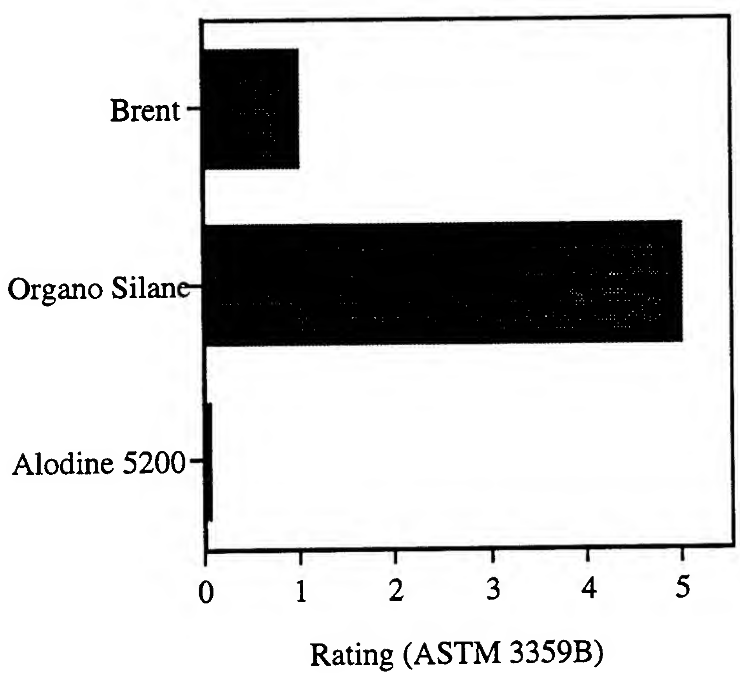


Figure 35. Dry adhesion ratings for unexposed aluminum 7039 panels (greater is better).

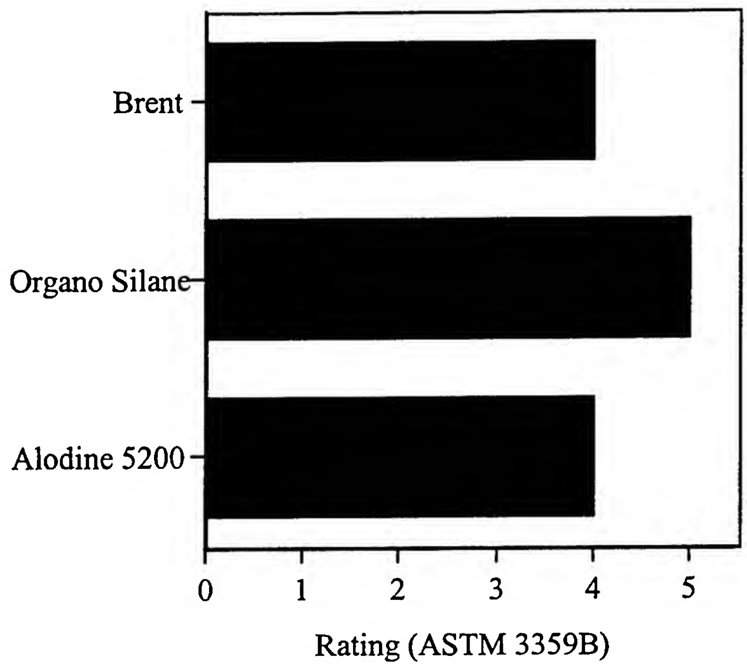


Figure 36. Dry adhesion ratings for unexposed aluminum 6061 panels (greater is better).

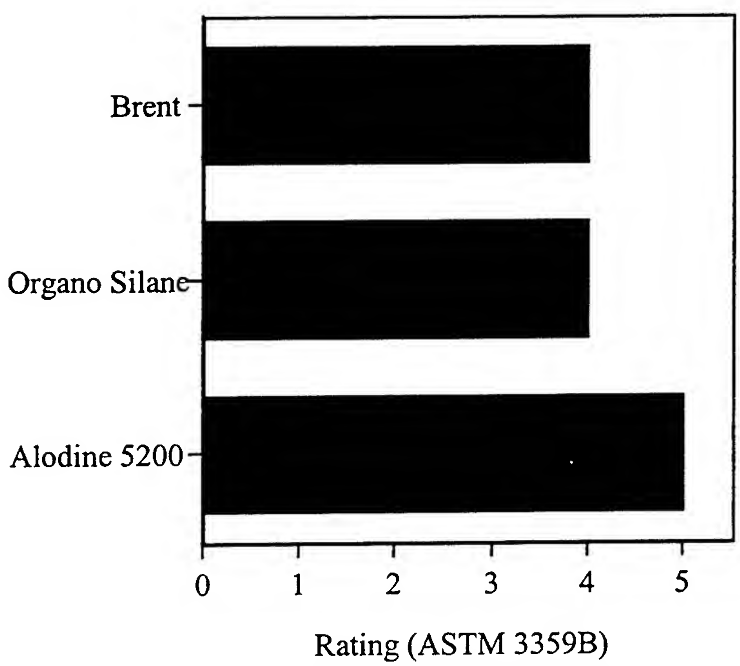


Figure 37. Dry adhesion ratings for unexposed Al 5083 headlight guards (greater is better).

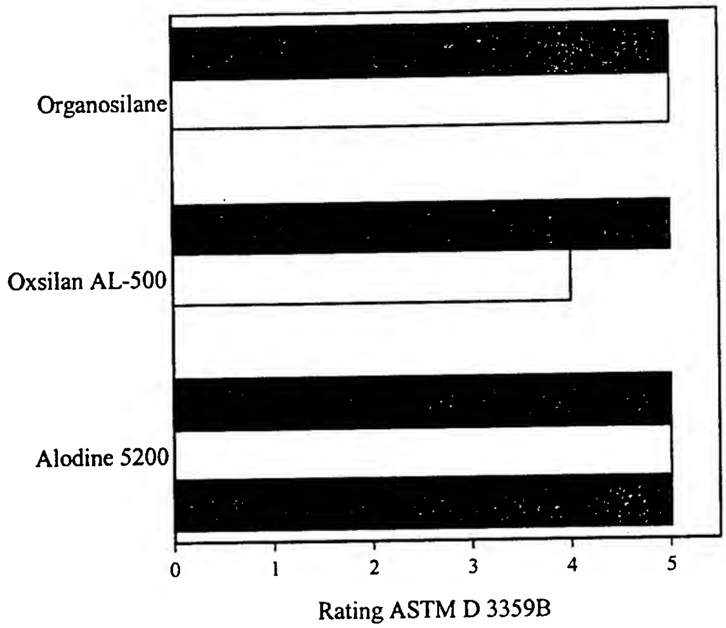


Figure 38. Dry adhesion ratings for salt fog-exposed Al 5083 panels (greater is better).

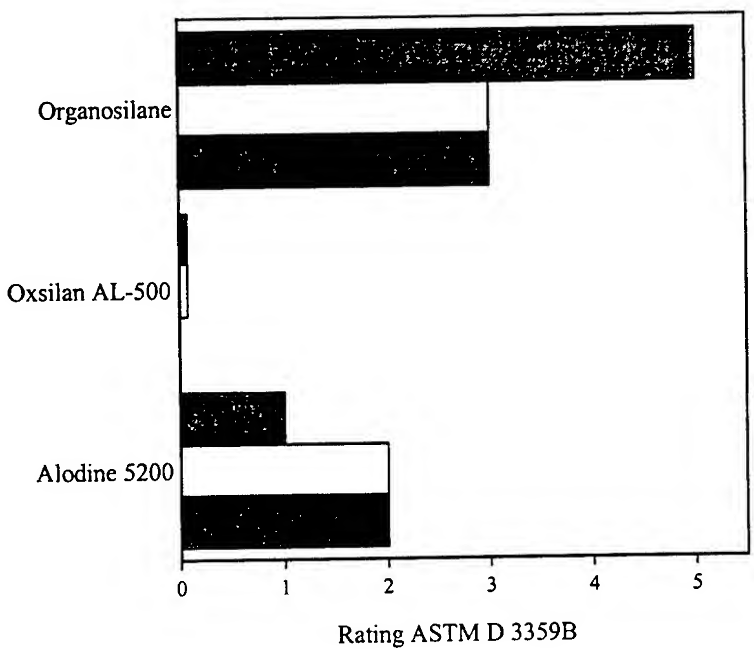


Figure 39. Dry adhesion ratings for salt fog-exposed Al 7039 panels (greater is better).

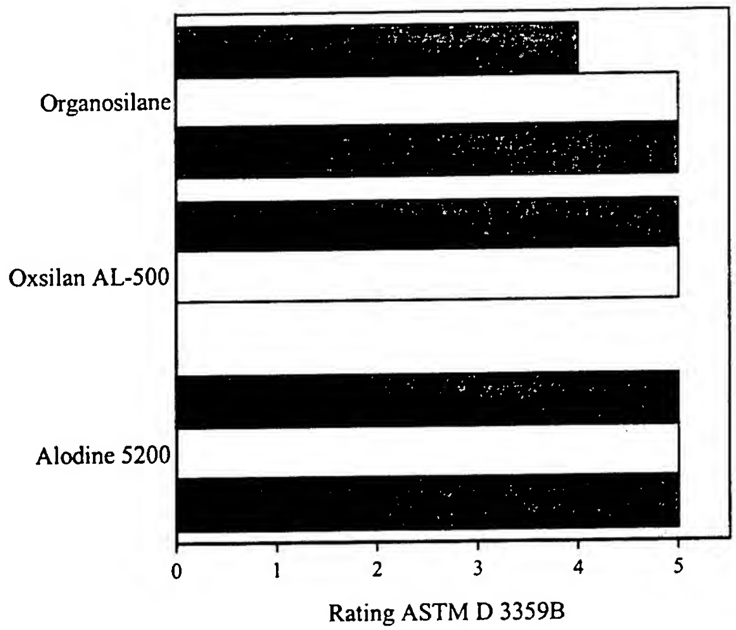


Figure 40. Dry adhesion ratings for salt fog-exposed Al 6061 panels (greater is better).

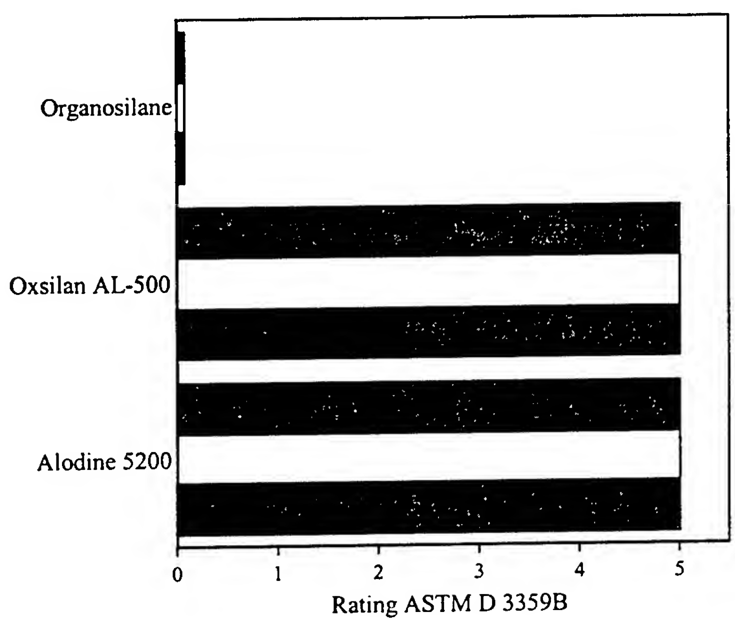


Figure 41. Dry adhesion ratings for GM 9540P [5] exposed Al 5083 panels (greater is better).

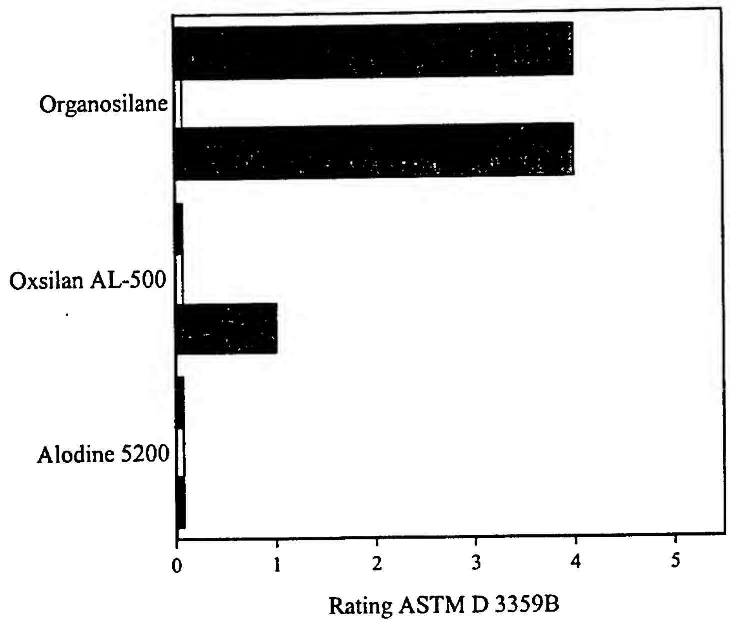


Figure 42. Dry adhesion ratings for GM 9540P [5] exposed Al 7039 panels (greater is better).

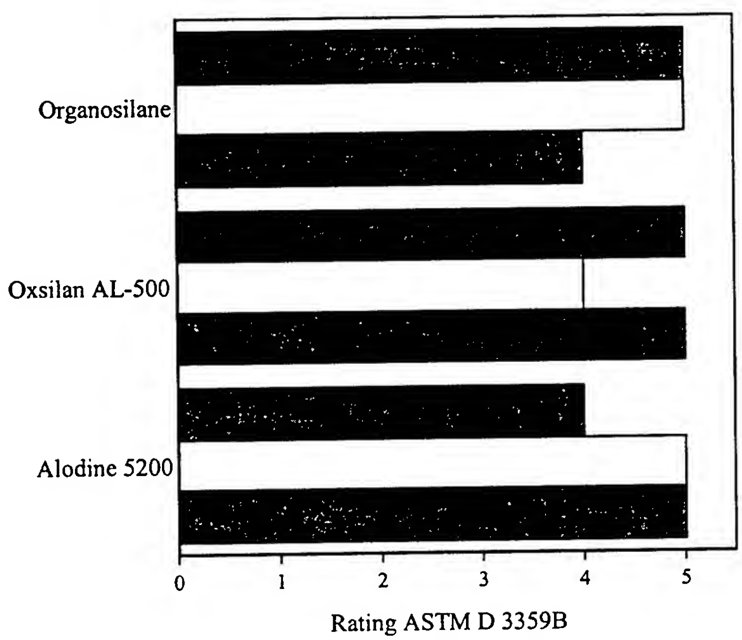


Figure 43. Dry adhesion ratings for GM 9540P [5] exposed Al 6061 panels (greater is better).

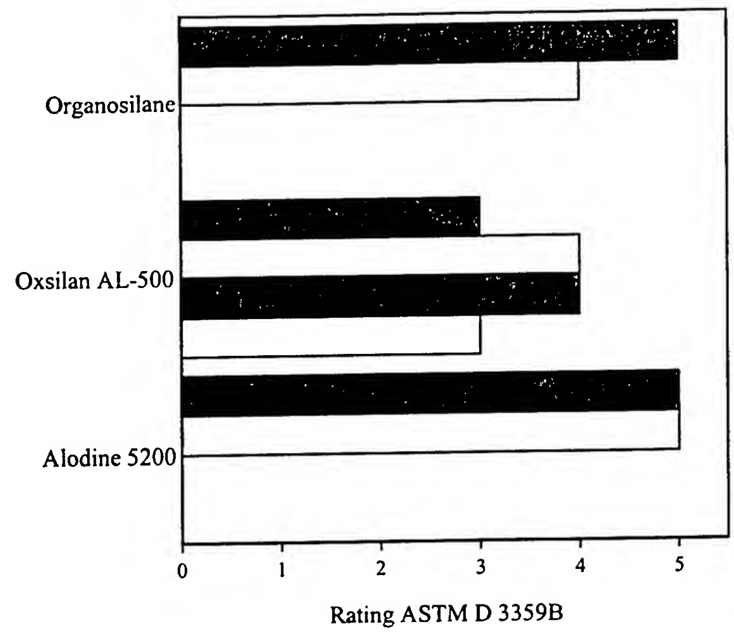


Figure 44. Dry adhesion ratings for GM 9540P [5] Al 5083 headlight guards (greater is better).

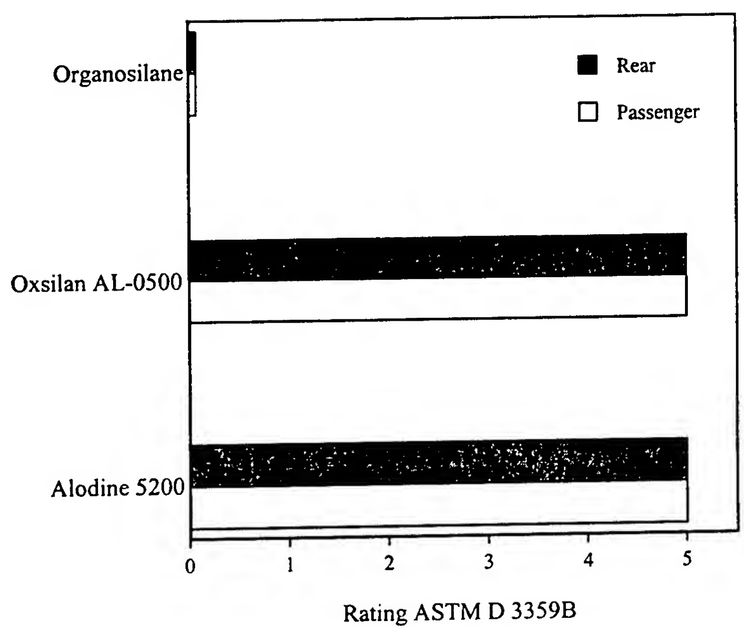


Figure 45. Dry adhesion ratings for vehicle-mounted Al 5083 panels after seven-phases test track exposure (greater is better).

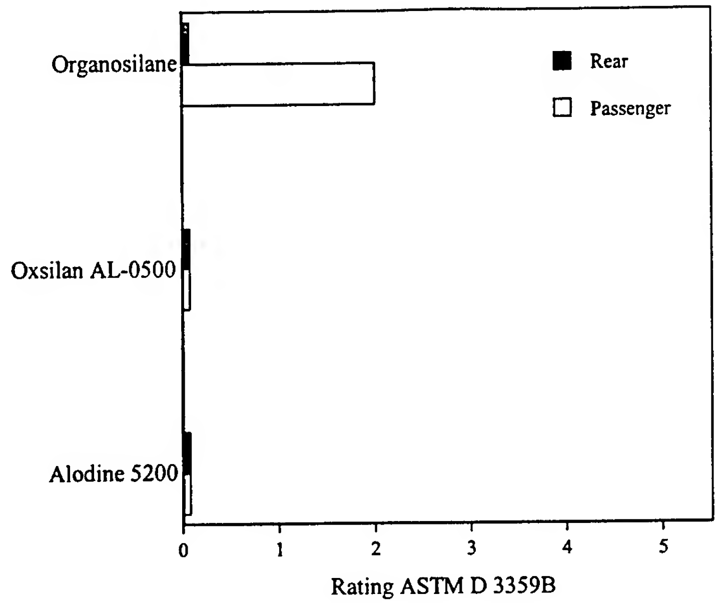


Figure 46. Dry adhesion ratings for vehicle-mounted Al 7039 panels after seven-phases test track exposure (greater is better).

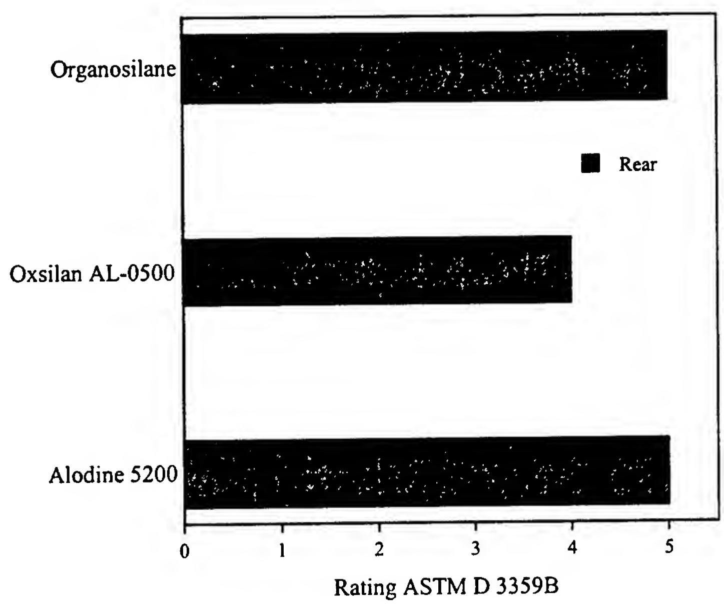


Figure 47. Dry adhesion ratings for vehicle-mounted Al 6061 panels after seven-phases test track exposure (greater is better).

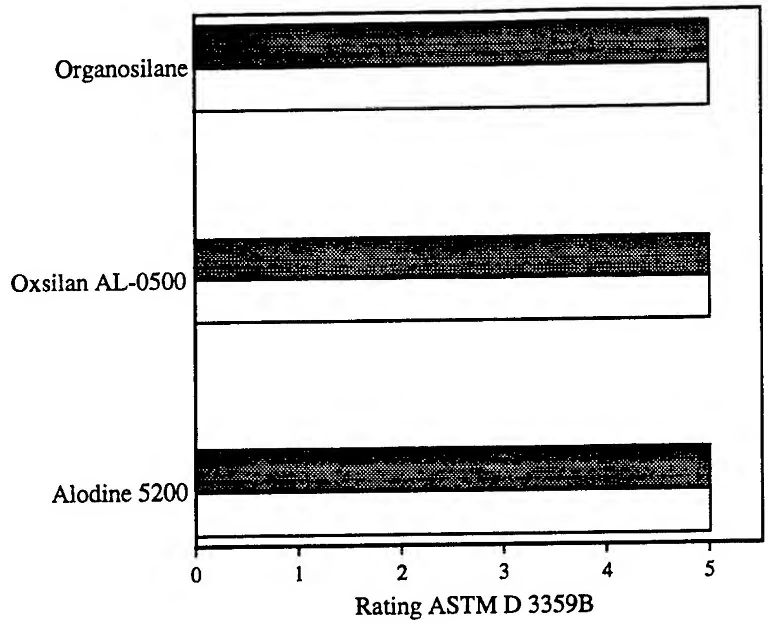


Figure 48. Dry adhesion ratings for vehicle-mounted Al 5083 taillight guards after seven-phases test track exposure (greater is better).

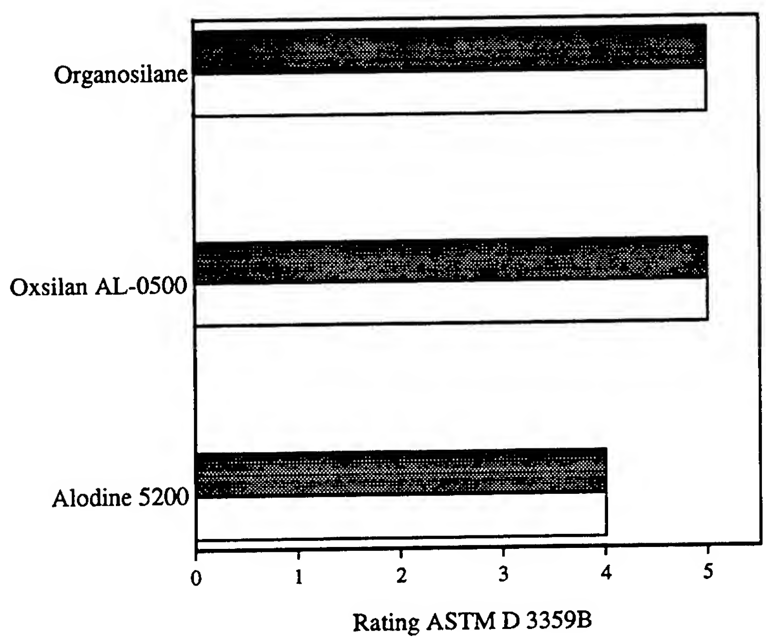


Figure 49. Dry adhesion ratings for vehicle-mounted Al 5083 bilge cover after seven-phases test track exposure (greater is better).

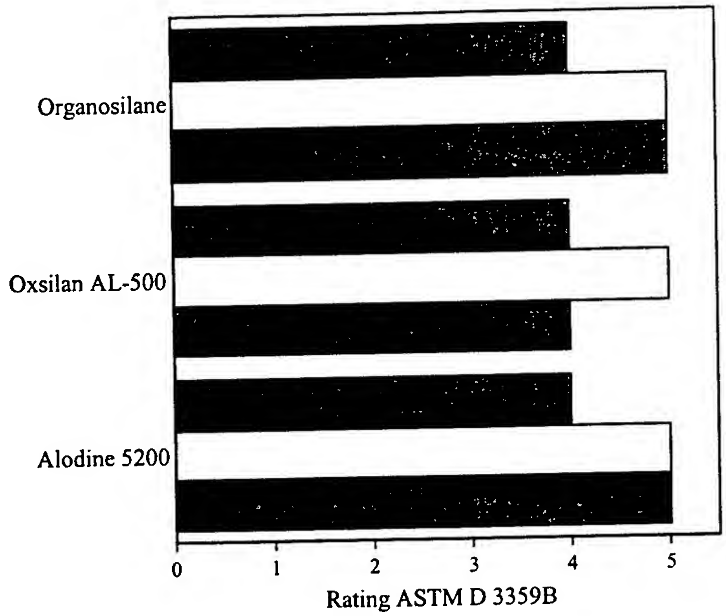


Figure 50. Dry adhesion ratings for Bradley-mounted Al 5083 panels after 4000-mi durability exposure at Camp Roberts, CA (greater is better).

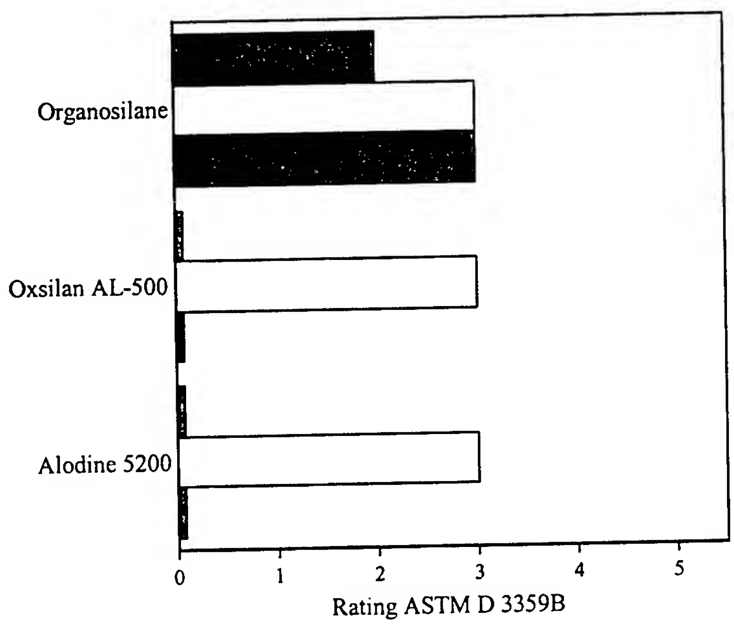


Figure 51. Dry adhesion ratings for Bradley-mounted Al 7039 panels after 4000-mi durability exposure at Camp Roberts, CA (greater is better).

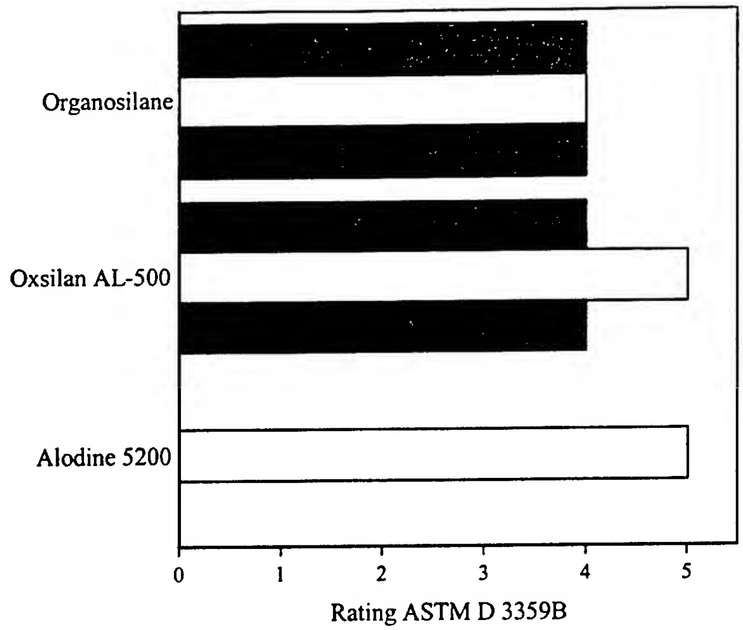


Figure 52. Dry adhesion ratings for Bradley-mounted Al 6061 panels after 4000-mi durability exposure at Camp Roberts, CA (greater is better).

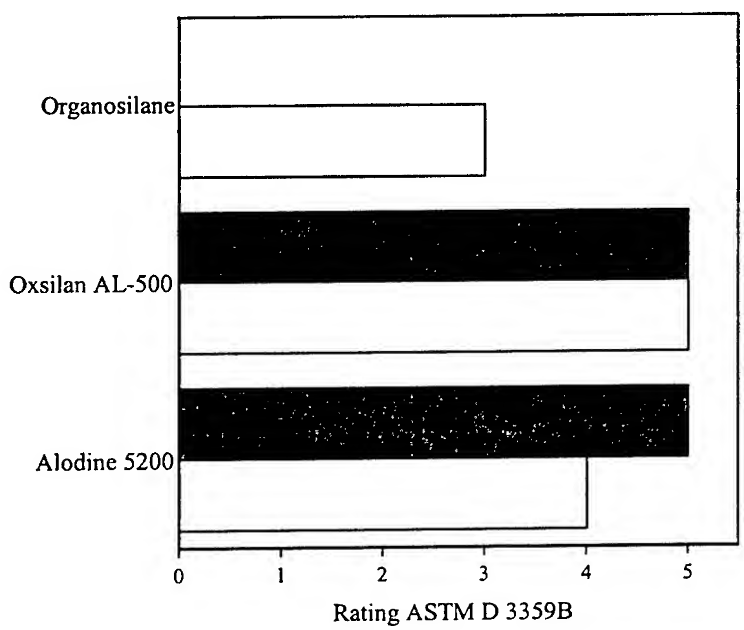


Figure 53. Dry adhesion ratings for mixed Al 5083 Bradley components after 4000-mi durability exposure at Camp Roberts, CA (greater is better).

Table 1. Panel and component designation—Brent Oxsilan AL-0500.

Part No.	Name	Primer	Topcoat
12317017-1	Guard, taillight	MIL-P-53022	MIL-C-53039
12369326	Bracket, headlight right	MIL-P-53022	MIL-C-53039
5B-1, -2, -3	(3) 5083 BFV coupons (one hole)	MIL-P-53022	MIL-C-53039
6B-1, -2, -3	(3) 6061 BFV coupons (one hole)	MIL-P-53022	MIL-C-53039
7B-1, -2, -3	(3) 7039 BFV coupons (one hole)	MIL-P-53022	MIL-C-53039
12369237 L2	Guard, headlight right	MIL-P-53022	MIL-C-53039
5L-27 thru -32	(7) 5083, headlight right	MIL-P-53022	MIL-C-53039
6L-27 thru -32	(7) 6061 lab coupons	MIL-P-53022	MIL-C-53039
7L-27 thru -32	(7) 7039 lab coupons	MIL-P-53022	MIL-C-53039
12317017-1 F1	Guard taillight	MIL-P-53022	MIL-C-53039
12385421 F2	Cover, access bilge pump	MIL-P-53022	MIL-C-22750
5F-13, -14, -15	(3) 5083 FMTV coupons (two holes)	MIL-P-53022	MIL-C-53039
6F-13, -14, -15	(3) 6061 FMTV coupons (two holes)	MIL-P-53022	MIL-C-53039
7F-13, -14, -15	(3) 7039 FMTV coupons (two holes)	MIL-P-53022	MIL-C-53039

Notes: MIL-P-53022 is reference [10].
MIL-C-53039 is reference [11].
MIL-C-22750 is reference [12].

Table 2. Panel and component designation—Alodine 5200.

Part No.	Name	Primer	Topcoat
12317017-2	Guard, taillight	MIL-P-53022	MIL-C-53039
12368237	Bracket, headlight right	MIL-P-53022	MIL-C-53039
5B-4, -5, -6	(3) 5083 BFV coupons (one hole)	MIL-P-53022	MIL-C-53039
6B-4, -5, -6	(3) 6061 BFV coupons (one hole)	MIL-P-53022	MIL-C-53039
7B-4, -5, -6	(3) 7039 BFV coupons (one hole)	MIL-P-53022	MIL-C-53039
12369237 L1	Guard, headlight right	MIL-P-53022	MIL-C-53039
5L-20 thru -26	(7) 5083, lab coupons	MIL-P-53022	MIL-C-53039
6L-20 thru -26	(7) 6061 lab coupons	MIL-P-53022	MIL-C-53039
7L-20 thru -26	(7) 7039 lab coupons	MIL-P-53022	MIL-C-53039
12317017-1 F2	Guard taillight	MIL-P-53022	MIL-C-53039
12385421 F1	Cover, access bilge pump	MIL-P-53022	MIL-C-22750
5F-10, -11, -12	(3) 5083 FMTV coupons (two holes)	MIL-P-53022	MIL-C-53039
6F-10, -11, -12	(3) 6061 FMTV coupons (two holes)	MIL-P-53022	MIL-C-53039
7F-10, -11, -12	(3) 7039 FMTV coupons (two holes)	MIL-P-53022	MIL-C-53039

Notes: MIL-P-53022 is reference [10].
MIL-C-53039 is reference [11].
MIL-C-22750 is reference [12].

Table 3. Panel and component designation—Organosilane.

Part No.	Name	Primer	Topcoat
12369239	Guard, headlight left	MIL-P-53022	MIL-C-53039
5B-7, -8, -9	(3) 5083 BFV coupons (one hole)	MIL-P-53022	MIL-C-53039
6B-7, -8, -9	(3) 6061 BFV coupons (one hole)	MIL-P-53022	MIL-C-53039
7B-7, -8, -9	(3) 7039 BFV coupons (one hole)	MIL-P-53022	MIL-C-53039
12369237 L3	Guard, headlight right	MIL-P-53022	MIL-C-53039
5L-33 thru -39	(7) 5083, headlight right	MIL-P-53022	MIL-C-53039
6L-33 thru -39	(7) 6061 lab coupons	MIL-P-53022	MIL-C-53039
7L-33 thru -39	(7) 7039 lab coupons	MIL-P-53022	MIL-C-53039
12317017-1 F3	Guard taillight	MIL-P-53022	MIL-C-53039
12385421 F3	Cover, access bilge pump	MIL-P-53022	MIL-C-22750
5F-16, -17, -18	(3) 5083 FMTV coupons (two holes)	MIL-P-53022	MIL-C-53039
6F-16, -17, -18	(3) 6061 FMTV coupons (two holes)	MIL-P-53022	MIL-C-53039
7F-16, -17, -18	(3) 7039 FMTV coupons (two holes)	MIL-P-53022	MIL-C-53039

Notes: MIL-P-53022 is reference [10].
MIL-C-53039 is reference [11].
MIL-C-22750 is reference [12].

Table 4. Surface preparation and processing parameters for Cape Code Organosilane.

Chemistry	Technique	Concentration	Temperature	Residence Time
Oakite NST Alkaline Cleaner	Immersion	~10%	55 °C	3 min
Oakite 360L Alkaline Etch	Immersion	~5%	61 °C	1 min
DI Water Rinse	Spray	N/A	Ambient	As needed to thoroughly rinse
Oakite LNC Deoxidizer	Immersion	~16%	Ambient	4 min
DI Water Rinse	Spray	N/A	Ambient	As needed to thoroughly rinse
Organosilane	Immersion	316.5-g initiator 1240-mL A1 310-mL A2 49.6-gal DI water	Ambient	10 min
Cure	Oven	N/A	93 °C	60 min

Notes: DI = Deionized.
N/A = Not Applicable.

Table 5. Surface preparation and processing parameters for Brent Oxsilan AL-0500.

Chemistry	Technique	Concentration	Temperature	Residence Time
Chem Clean 1220	Immersion	~5%	49 °C	1 min
DI Water Rinse	Spray	N/A	Ambient	~50 s
Oxsilan AL-0500	Immersion	1680-mL A 2900-mL B 46.4-g DI water	38 °C	2 min
DI Water Rinse	Spray	N/A	Ambient	~30 s
Dry	Oven	N/A	65 °C	2 min

Table 6. Surface preparation and processing parameters for Henkel Alodine 5200.

Chemistry	Technique	Concentration	Temperature	Residence Time
Ridoline 298	Immersion	~6%	54.4 °C (130 °F)	3 min
DI Water Rinse	Spray	N/A	Ambient	~50 s
Deoxidizer HX-357	Immersion	~6%	Ambient	3 min
DI Water Rinse	Spray	N/A	Ambient	~40 s
Alodine 5200	Immersion	~3%	35 °C (95 °F)	1 min in solution followed by 2 min in air
DI Water Rinse	Spray	N/A	Ambient	As needed to thoroughly rinse
Dry	Oven	N/A	93.3 °C (200 °F)	5 min

Table 7. Evaluation of painted or coated specimens subjected to corrosive environments—ASTM D1654 [13].

Rating of Failure at Scribe (Procedure A)		
Representative Mean Creepage From Scribe		
Millimeters	Inches (approximate)	Rating Number
Over 0	0	10
Over 0 to 0.5	0 to 1/64	9
Over 0.5 to 1.0	1/64 to 1/32	8
Over 1.0 to 2.0	1/32 to 1/16	7
Over 2.0 to 3.0	1/16 to 1/8	6
Over 3.0 to 5.0	1/8 to 3/16	5
Over 5.0 to 7.0	3/16 to 1/4	4
Over 7.0 to 10.0	1/4 to 3/8	3
Over 10.0 to 13.0	3/8 to 1/2	2
Over 13.0 to 16.0	1/2 to 5/8	1
Over 16.0 to more	5/8 to more	0

Table 8. GM 9540P [5] cyclic corrosion test details.

Interval	Description	Interval time (min)	Temperature (±3 °C)
1	Ramp to Salt Mist	15	25
2	Salt Mist Cycle	1	25
3	Dry Cycle	15	30
4	Ramp to Salt Mist	70	25
5	Salt Mist Cycle	1	25
6	Dry Cycle	15	30
7	Ramp to Salt Mist	70	25
8	Salt Mist Cycle	1	25
9	Dry Cycle	15	30
10	Ramp to Salt Mist	70	25
11	Salt Mist Cycle	1	25
12	Dry Cycle	15	30
13	Ramp to Humidity	15	49
14	Humidity Cycle	480	49
15	Ramp to Dry	15	60
16	Dry Cycle	480	60
17	Ramp to Ambient	15	25
18	Ambient Cycle	480	25

Table 9. GM 9540P [5] chamber mass loss calibration details.

For 1/6-in-thick mass loss specimens					
Coupon No.	Duration (cycles)	Mass Loss Target Range (g)	Initial Mass (g)	Post-Exposure Mass (g)	Actual Mass Loss (g)
887J	8	0.874–1.274	15.87	15.05	0.82 (-)
890J	8	0.874–1.274	15.93	15.01	0.92
893J	8	0.874–1.274	15.88	14.91	0.97
896J	8	0.874–1.274	16.08	14.94	1.14
888J	16	1.574–1.974	15.88	13.96	1.92
891J	16	1.574–1.974	15.87	13.99	1.88
894J	16	1.574–1.974	15.84	13.81	2.03 (+)
897J	16	1.574–1.974	15.8	13.98	1.82
889J	40	3.378-3.978	16.02	12.6	3.42
892J	40	3.378-3.978	15.82	12.79	3.03 (-)
895J	40	3.378-3.978	16.01	12.33	3.68
898J	40	3.378-3.978	16.03	12.41	3.62

Table 10. ATC test track durability test events.

Gravel Road	The gravel road course imparts coating damage caused by stone impingement on the underbody of the vehicle. The gravel road also provides a high-frequency, low-amplitude input on the underbody and other body components, which may act as abrasive forces. The road surface is compacted gravel maintained by grading. The gravel road is traveled at varying speeds up to 45 mph consistent with safe vehicle operation.
Rolling Hills Course	The rolling hills course subjects the vehicle to twisting and turning motions associated with traveling on cross-country terrain. The course is designed to provide short, closely spaced grades. As a vehicle alternates between inclines and declines on this course, the engine and power train are subjected to rapid variations in loading. The surface consists of crushed stone compacted with stone dust binder.
Belgian Block Course	This portion of the test subjects the vehicle to intermediate frequency and force inputs typical of trails. The facility is paved with unevenly laid granite blocks forming an undulating surface. It duplicates the rough cobblestone road found in many parts of the world. The course is useful as a standard rough road for accelerated tests of wheeled vehicles, and is generally included in courses for vibration studies. The motion imparted to a vehicle is a random combination of roll and pitch and high-frequency vibrations imparted by the granite paving blocks.
High-Speed Test Track	The high-speed test track induces high-frequency vibration forces on joints and strains underbody components. These forces may cause some abrasive action. Higher speeds may also force contaminants into crevice areas. The track is an evenly paved surface capable of allowing continuous travel of the vehicle at 50 mph.
Frame Twister	The frame twister provides a dynamic flexural input to the vehicle at the beginning and end of the test. The frame twister is executed in the beginning of the test to flex the joints and allow initiation of corrosion in broken joints and seams early in the test. The frame twister is executed at the end of the test to fully stress all structural components to ensure integrity after the cumulative corrosion. The frame twister is designed to deflect the opposite wheels of the vehicle in alternately contrary directions. This is accomplished by dividing the road in half and creating two separate series of hills (waves) on either side. At each peak's maximum point the wheel is raised 2 ft above the average height. At each valley's minimum point, the wheel is lowered 2 ft below the average height.

Table 11. ATC test track corrosive application test events (driving).

Grit Trough	The grit trough introduces small particles into various crevices and joints on the underside of the vehicle. Grit accumulates in the crevices and on remote surfaces. The accumulated grit, or poultice, increases the time of wetness underneath its surface and keeps contaminants against the surface of the vehicle. The grit also adds some abrasive stresses to the coatings and other material systems they contact.
Salt Splash/Mist	The salt splash/mist facilities applies a salt spray solution to all surfaces of the top and sides of the vehicle as well as to the bottom of the vehicle as would be seen during normal driving conditions. As the name implies, it consists of two facilities: a shallow trough of salt water which splashes the vehicle underside and a booth in which the salt water is misted over the vehicle. The salt splash trough exposes the undercarriage of the vehicle to high concentration salt solutions that will be present on roadways, typically from road deicing salts. The application includes exposure to fine mists from elevated speed travel. The salt mist booth applies the corrosive salt solution to all areas of the vehicle by creating a fine mist all around the vehicle.

Table 12. ATC test track accelerated corrosion event (static).

Humidity Chamber	The purpose of the humidity chamber is to create high temperature and humidity conditions that will accelerate the natural corrosion process. In effect, the booth accelerates the reaction of the contaminants applied by the different test events with any exposed material on the vehicle. The temperature is held at 120 °F, ±5°. The relative humidity is maintained at 100% in a condensing state. The resulting water fog provides a condensation rate of 1-2 mL/hour in collection devices having a horizontal collection area of 80 cm^2. Circulation fans provide a moderate flow of the high humidity air throughout the chamber.
Ambient Storage	During many portions of the test duration, the vehicles are not participating in any test events. During these times, the vehicle is stored at ambient conditions in a sheltered location. There is no specific requirement for the timing or duration of ambient storage. Prior to storage time exceeding four days, the vehicle is washed to remove contaminants and stored in a low humidity, preferably cool environment to minimize corrosion.

Table 13. ATC test track accelerated vehicle maintenance test events.

Equipment Exercise	At the end of each test phase or as necessary to validate functionality, critical systems are exercised. This is both to ensure that they continue to be operational and to incorporate into the durability test any effects of accumulated grit, debris, and corrosion.
Vehicle Washing	The vehicle is washed twice during each test phase (simulated year). Washing consists of high-pressure potable water wash immediately prior to the durability test events. If necessary, local areas of heavily caked mud may be removed at any time. This prevents build-up of excessive debris that may inhibit corrosion.

Table 14. Representative daily driving test cycle.

Laps	Event	Miles
–	Grit Trough	–
3	Gravel Road	6.3
–	Grit Trough	–
3	Gravel Road	6.3
–	Grit Trough	–
5	Belgian Block Access to Belgian Block	3.5 2.0
–	Salt Splash/Mist	–
5	High Speed Test Track	5.0
–	Grit Trough	–
3	Rolling Hills Access to Rolling Hills	2.4 1.7
–	Grit Trough	–
5	Belgian Block Access to Belgian Block	3.5 2.0
–	Grit Trough	–
4	High Speed Test Track	4.0
–	Salt Splash/Mist	–
7	Rolling Hills Access to Rolling Hills	5.6 1.7
–	Grit Trough	–
3	Gravel Road	6.3
–	Grit Trough	–
5	Belgian Block Access to Belgian Block	3.5 2.0
–	Grit Trough	–
3	Rolling Hills Access to Rolling Hills	2.4 1.7
–	Grit Trough	–
4	High Speed Test Track	4.0

Note: 15 cycles/phase with frame twister after second and 22nd phases.

Table 15. Wet adhesion rating—method ASTM D3359A [6].

Method A: Wet Adhesion	
Rating	Description of Coating After Tape Removal
5[a]	No peeling or removal
4	Trace peeling or removal along scribes
3	Jagged removal along scribes up to 1/16 in (1.6 mm) on either side
2	Jagged removal along most of the scribes up to 1/8 in (3.2 mm) on either side
1	Removal from most of the area between the scribes under the tape
0	Removal beyond the area of the scribes

[a]Passes military performance criteria.

Table 16. Dry adhesion rating—method ASTM D3359B [6].

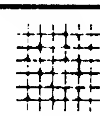
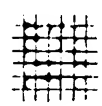
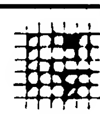
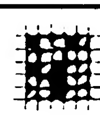
Classification	Surface of cross-cut area from which flaking has occured. (Example for 6 parallel cuts)
5	None
4	
3	
2	
1	

Table 17. Laboratory conditions for pull-off adhesion—ASTM D4541 [7].

Adhesive Type	Cyanoacrylate
Cure time (hours)	24
Temperature (°C)	25
Percent Relative Humidity	31
Substrate Material	Aluminum 5083/7039
Primer	MIL-P-5302 [10]
Topcoat	MIL-C-53039 [11]
Total Coating Thickness (mils)	~4.0

Table 18. Pull-off adhesion results for unexposed panels.

Adhesion—ASTM D4541 [7] Initial					
Al Alloy	Treatment	Specimen ID	Adhesion (psi)	Failure Mode	Specimen Thickness (in)
5083	Alodine 5200	5L-26	3100	Interlayer	0.3750
5083	Oxsilan AL-500	5L-32	3090	Interlayer	0.3750
5083	Organosilane	5L-39	3410	Interlayer	0.3750
7039	Alodine 5200	7L-26	630	Substrate	0.2500
7039	Oxsilan AL-500	7L-32	520	Substrate	0.2500
7039	Organosilane	7L-39	2620	Interlayer	0.2500

Table 19. Pull-off adhesion results for 3000-hr salt fog-exposed panels and components.

Adhesion—ASTM D4541 [7] at 120 cycles GM 9540P [5]					
Al Alloy	Treatment	Specimen ID	Adhesion (psi)	Failure Mode	Specimen Thickness (in)
5083	Alodine 5200	5L-23	2775	Interlayer	0.3750
5083	Oxsilan AL-500	5L-29	2790	Interlayer	0.3750
5083	Organosilane	5L-36	2190	Substrate	0.3750
7039	Alodine 5200	7L-23	510	Substrate	0.2500
7039	Oxsilan AL-500	7L-29	2500	Interlayer	0.2500
7039	Organosilane	7L-37	1950	Interlayer/Substrate	0.2500
5083	Alodine 5200	12369237 L1	2520	Interlayer	0.2500
5083	Oxsilan AL-500	12369237 L2	2510	Interlayer	0.2500
5083	Organosilane	12369237 L3	2320	Interlayer	0.2500

Table 20. Pull-off adhesion results for 120-cycle GM 9540P [5] exposed panels and components.

Adhesion—ASTM D4541 [7] at 3000-hr ASTM B117 [4]					
Al Alloy	Treatment	Specimen ID	Adhesion (psi)	Failure Mode	Specimen Thickness (in)
5083	Oxsilan AL-500	5L-27	2250	Interlayer	0.3750
5083	Organosilane	5L-33	2600	Interlayer	0.3750
7039	Alodine 5200	7L-20	700	Substrate	0.2500
7039	Oxsilan AL-500	7L-27	520	Substrate	0.2500
7039	Organosilane	7L-33	2100	Interlayer/Adhesive	0.2500

Table 21. Pull-off adhesion results for ATC test track-exposed panels and components.

Adhesion—ASTM D4541 [7] at seven phases ATC test track					
Al Alloy	Treatment	Specimen ID	Adhesion (psi)	Failure Mode	Specimen Thickness (in)
5083P	Oxsilan AL-500	5F-13	2310	Interlayer	0.3750
5083P	Organosilane	5F-16	1250	Substrate	0.3750
5083R	Oxsilan AL-500	5F-14	2340	Interlayer	0.3750
5083R	Organosilane	5F-17	1710	Substrate	0.3750
7039P	Alodine 5200	7F-11	2180	Interlayer/Substrate	0.2500
7039P	Oxsilan AL-500	7F-14	540	Substrate	0.2500
7039P	Organosilane	7F-18	1310	Substrate/Interlayer	0.2500
7039R	Alodine 5200	7F-10	2100	Interlayer/Substrate	0.2500
7039R	Oxsilan AL-500	7F-13	1720	Substrate/Interlayer	0.2500
7039R	Organosilane	7F-17	2000	Interlayer/Substrate	0.2500
5083D	Alodine 5200	12317017-1 F2	2490	Interlayer	0.2500
5083D	Oxsilan AL-500	12317017-1 F1	2160	Interlayer	0.2500
5083P	Organosilane	12317017-1 F3	2120	Interlayer	0.2500

Table 22. Pull-off adhesion results for Bradley-mounted panels and components from Camp Roberts, CA.

Adhesion—ASTM D4541 [7] at 94 days and 4000 durability mi (actual fielded vehicles, Camp Roberts, CA)					
Al Alloy	Treatment	Specimen ID	Adhesion (psi)	Failure Mode	Specimen Thickness (in)
5083	Oxsilan AL-500	5B-2	2550	Interlayer	0.3750
5083	Oxsilan AL-500	5B-3	3030	Interlayer	0.3750
5083	Alodine 5200	5B-4	2780	Interlayer/Substrate	0.3750
5083	Alodine 5200	5B-5	2570	Interlayer	0.3750
5083	Alodine 5200	5B-6	3000	Interlayer	0.3750
5083	Organosilane	5B-7	2090	Substrate/Interlayer	0.3750
5083	Organosilane	5B-8	2620	Interlayer	0.3750
5083	Organosilane	5B-9	2960	Interlayer	0.3750
7039	Oxsilan AL-500	7B-1	510	Substrate	0.2500
7039	Oxsilan AL-500	7B-2	2450	Interlayer	0.2500
7039	Oxsilan AL-500	7B-3	570	Substrate	0.2500
7039	Alodine 5200	7B-4	560	Substrate	0.2500
7039	Alodine 5200	7B-5	2620	Interlayer	0.2500
7039	Alodine 5200	7B-6	2290	Interlayer	0.2500
7039	Organosilane	7B-7	2270	Interlayer/Substrate	0.2500
7039	Organosilane	7B-8	2410	Interlayer/Substrate	0.2500
7039	Organosilane	7B-9	2410	Interlayer	0.2500
5083	Oxsilan AL-500	12317017-1	2520	Interlayer	0.2500
5083	Alodine 5200	12317017-2	2310	Interlayer	0.2500
5083	Alodine 5200	12369237	2590	Interlayer	0.3750
5083	Organosilane	12369239	2550	Interlayer	0.3750
5083	Oxsilan AL-500	12369326	>3500	Interlayer	0.5000

Table 23. Conical mandrel bend results for Bradley-mounted AL 6061 panels and components from Camp Roberts, CA.

Panel Designation	Pretreatment	Crack Length (in)[a]	% Coating Elongation	Demalination Distance (in)[a]
6B-1	Oxsilan AL-500	Full Length	N/A	0.1875
6B-2	Oxsilan AL-500	Full Length	N/A	0.1250
6B-3	Oxsilan AL-500	4.1875	4.56	0.3125
6B-5	Alodine 5200	Full Length	N/A	0.4375
6B-7	Organosilane	Full Length	N/A	0.0313
6B-8	Organosilane	5.375	3.90	0.1875
6B-9	Organosilane	5.5625	3.66	0.0625

[a]Measured from small end of cone.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2001	Final, November 1999—December 2000

4. TITLE AND SUBTITLE
Examination of Nonchromate Conversion Coatings for Aluminum Armor From Three Final Candidates Using Accelerated Corrosion and Adhesion Test Methods

5. FUNDING NUMBERS
LIFX02

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WM-MC
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2601

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
U.S. Army Tank-Automotive Research, Development, and Engineering Center, Warren, MI 48397

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
*U.S. Army Aberdeen Test Center, Aberdeen Proving Ground, MD 21005

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT*(Maximum 200 words)*
This study examines the effectiveness of three final candidate nonchromate conversion coatings on aluminum alloys 5083, 7039, and 6061 coated with standard solvent-based Chemical Agent Resistant Coating (CARC) system. The nonchromate conversion coatings examined were: Cape Cod Organosilane, Brent Oxsilan AL-0500, and Henkel Alodine 5200. Evaluation methods included: American Society for Testing and Materials (ASTM) standard B117 (ASTM. "Standard Method of Salt Spray [Fog] Testing." ASTM B117, West Conshohocken, PA, 1990) salt fog, General Motors (GM) 9540P (GM. "Accelerated Corrosion Test; GM 9540P." GM 9540P, GM Engineering Standards, 1997) cyclic salt spray, ASTM D3359A (ASTM. "Standard Test Methods for Measuring Adhesion by Tape Test." ASTM D3359, West Conshohocken, PA, 1987) wet adhesion, ASTM D3359B dry adhesion, ASTM D4541 (ASTM. "Standard Test Method for Pull-Off Strength of Coated Specimens Subjected to Corrosive Environments." ASTM D4541, West Conshohocken PA, 1989) pull-off adhesion, and exposure at the U.S. Army Aberdeen Test Center (ATC) automotive test track. Specimens examined consisted of flat test panels as well as actual components used in M2/M3 Bradley Fighting Vehicles Systems. Additional panels and components were exposed for 4000 mi on actual fielded Bradleys at Camp Roberts, CA, and examined after exposure for degradation and adhesion. The ultimate goal of this study is to choose the best overall substitute for hexavalent chromium based Alodine 1200 which is currently in use and is known to be harmful to the environment and a health hazard.

14. SUBJECT TERMS
corrosion, chromate, nonchromate, conversion coating, aluminum, armor, salt fog, cyclic salt spray, adhesion, automotive test track

15. NUMBER OF PAGES
69

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
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